3.—The Merougil Creek Sub-Area

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Abstract

The second of a series of accounts dealing with investigations of the Kalgoorlie system (early Precambrian, metamorphism c.2700 m.y. age) to the west of Lake Lefroy, deals with the north-easternmost part of the area, called, for convenience, the Merougil Creek sub-area. The psammitic and ruditic metasediments here exposed show particularly well-preserved gross primary sedimentational structures, though microscopic evidence of clastic texture is lacking, the microtextures being modifications of original greywacke textures-semischist and schist textures. The lithologies are described, a stratigraphic sequence covering nearly 17,000 feet of sediments without igneous rock intercalations erected, and the depositional environment is deduced to be marine, offshore and piedmontine. Metamorphism has produced assemblages corresponding to Green Schist Facies throughout the sub-area: metasomatism is evident in this sub-area. Igneous rocks include those of the Red Hill-Kambalda ophiolite belt, containing both metabasalts and serpentinites, and the site of the recent major nickel ore discovery, made since this investigation was completed: porphyries and adamellitic microgranites. Special attention is paid to the nature of the boulders in the Merougil Creek conglomerates: to their provenance; to their deformation; and to the porphyroid metasomatism that appears to affect these conglomerates. In this sub-area we see evidence of shearing and homogenisation of polymictic conglomerates to produce porcellanous rocks, in which the boulders show tendency to merge with the matrix, which they have come, by a process of homogenisation, to resemble. This process is believed to be the incipient stage in the more extreme porphyroid metasomatism recognised in similar rocks to the south, at Bayley's Workings and at Widgiemooltha. The conglomerates affected by the metasomatism are believed to consist mainly of igneous porphyry, metasedimentary, or granite boulders. The structure of the area is homoclinal to the west of the Kambalda Ophiolite Belt, which has been shown in mining operations to have a dome structure, reflected in pillow facings. The facing of the rocks of the homocline is consistently westwards.

Introduction

The Merougil Creek outcrops of metasediments are bounded on either side by ridges of greenstone, comprising belts of ophiolitic rocks of basic to ultrabasic composition (Fig. 1). To the east lies the Red Hill-Kambalda belt and to the west, the Yilmia belt.[1] These residual ridges stand up above an area of low relief and poor exposure, corresponding to the outcrop of a thick sequence of metasediments. The actual exposure is negligible in this intervening strip, except in the creek itself, near to its outlet into Lake Lefroy, and along the shore of Lake Lefroy. Granite intrudes the greenstones of the Red Hill-Kambalda Ophiolite Belt to the east: and some of this granite is rimmed by quartz-albite porphyry, similar to the rocks that form discrete, irregular masses in the same belt. Most of the quartz-albite porphyries appear to be closely related to the granite bodies, and, at one point within the area mapped, there is an insensible gradation from porphyry into a microadamellite. Another suite of porphyries, of an intermediate character carrying hornblende, seems also to be present in this belt, but not to be related to the granite intrusions. The Yilmia Ophiolite Belt is devoid of granites, but does contain some albite-quartz porphyry bodies of igneous aspect, apparently late intrusions into the basic and ultrabasic rocks forming the ophiolite belt. Like the porphyries of the Kambalda locality, these appear to have suffered at least part of the effects of orogenic deformation and metamorphism. The Yilmia ophiolite belt is described by Doepel (1965) and in a brief introductory account (McCall and Doepel, 1969). The Red Hill-Kambalda Ophiolite Belt was only studied by Braybrooke and Middleton (1964) in a limited coastal area, and, while some of their results have been considered worth brief mention in the subsequent text, much more detailed information is now available, though unpublished, as a result of detailed surface and underground mapping by geologists of the Western Mining Corporation.

The metasediments between the greenstone belts are dominantly psammitic, and include coarse, polymictic conglomerates. The metasandstones are of metagreywacke character, and so is the sandy matrix of the conglomerates. The greywackes have mostly been converted to *semischists* (Williams, Turner and Gilbert, p. 205: Turner, 1968, p. 31). There are subordinate intercalations of pelites, of metasiltstone character—pelites of finer grain size do not seem to be represented, though they are present as minor intercalations within the Red Hill-Kambalda Ophiolite Belt, and in quite thick sequences to the west of the summit

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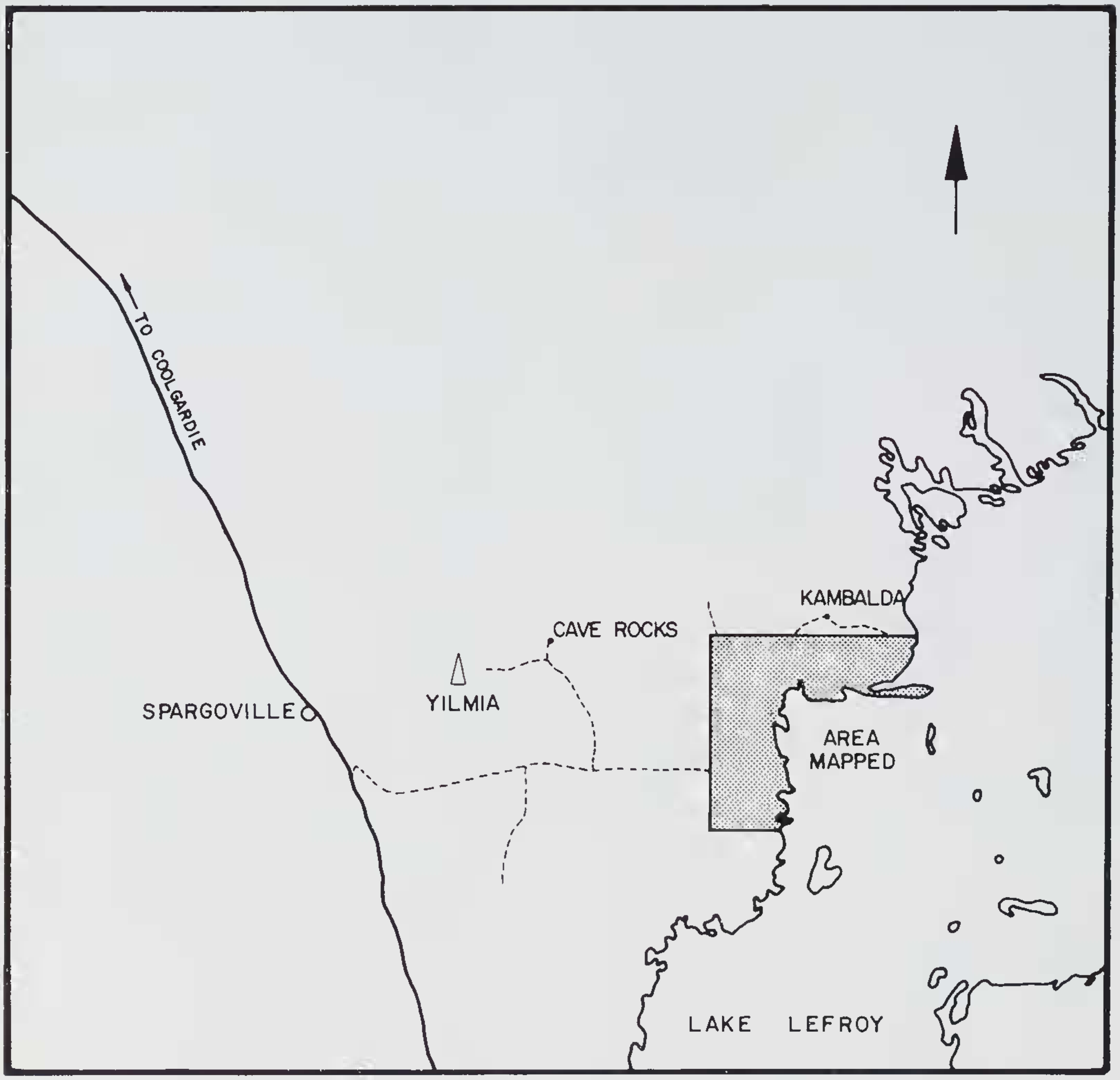
[1]Braybrooke and Middleton (1964) mapped as far as a reported greenstone outcrop near the lower dam on Merougil Creek (Fig. 2 inset): Doepel and McCall have re-examined the creek section from Yilmia Dam (near Cave Rocks) to this point, and it is apparent that the Merougil Beds continue westwards, probably to the fence line east of Yilmia Dam, where rocks of similar lithology still face west. No greenstone in place was recognised, and it seems possible that an outcrop of greenish weathered rock, believed to be the laterite capping of Plantagenet beds, was taken for greenstone. This account incorporates the results of the mapping by Doepel and McCall, and the Merougil Beds are thus considerably extended from the original thickness defined by Braybrooke and Middleton (op. cit.). A thickness of 16,000 feet given here includes this additional section; however, as noted in Part 1 of this series of accounts (McCall, in the press), it may be an overestimation.



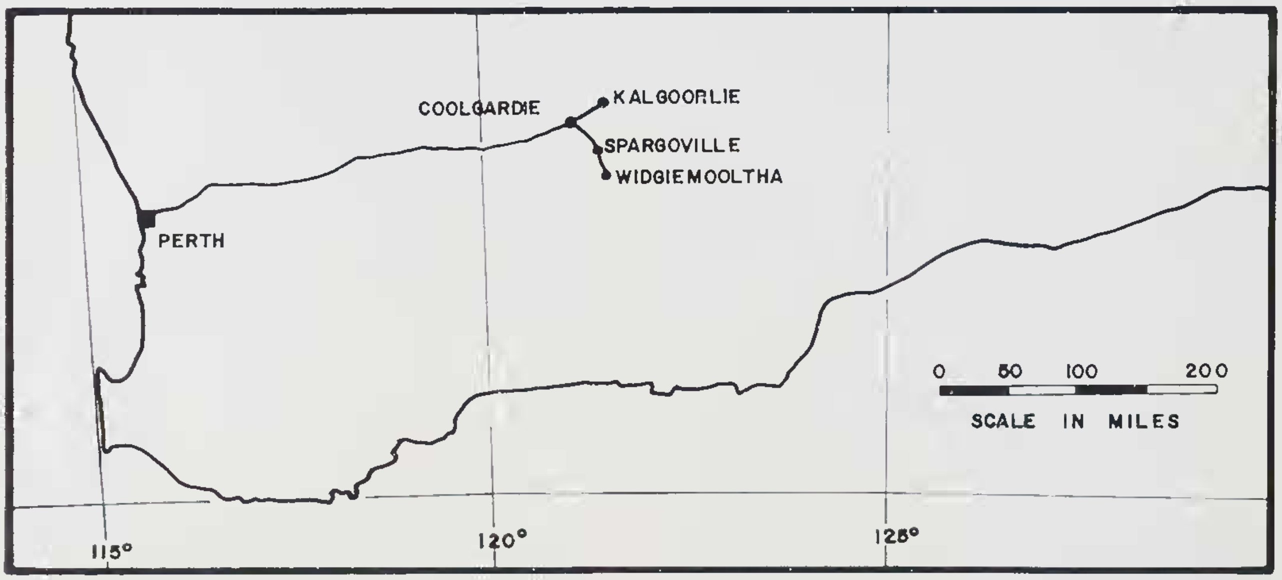


Figure 1.—Sketch map showing the location of the area discussed in this account.

of Yilmia Hill. The psammitic and psephitic rocks of the Merougil Beds (McCall, Braybrooke, Middleton and Muhling, 1967: McCall, *in the press*, part 1 of this series of accounts) have been found to extend, without any other rock type breaking the sequence, from the mouth of the Merougil Creek to a point just east of a north-south fence line, east of Yilmia Dam, where the last outcrop of them is cut by a small porphyry body. Except for this interruption, they are neither cut by porphyry bodies nor do they show intercalations of basic or ultrabasic meta-igneous rocks.

Near to the mouth of the creek a sequence of 5,700 feet of steeply disposed metasediments can be mapped in more or less continuous exposure. This sequence forms a homocline, showing consistent west facings, a regional strike of 310°, and a regional dip of 65° towards the south-west. A detailed subdivision can be made of this part of the Merougil Beds, but, to the west of the lower dam on Merougil Creek, the outcrop becomes sporadic and restricted to the creek bed in the upper part of the sequence: and what rocks are exposed in the creek bed are heavily kaolinised: it is thus impossible to make any detailed subdivision. The very definite west facing just west of Yilmia Dam, the intermittent exposure of similar rocks throughout the creek section, and stratigraphic considerations of a regional nature, suggest that the Merougil Beds *do* continue right through this section without interruption, though fine pelite intercalations might be obscured in the upper part of the section. They are believed to be overlain by the Cave Rocks Beds and Abattoir Line-Cave Rocks Ophiolite Belt, cut off on the west side from the Yilmia Ophiolite Belt by the Yilmia Dislocation.

The Merougil Beds were at one time thought to be in virtual strike continuity with the Kurrawang Conglomerates, and to be their stratigraphic equivalents (Cleverly, unpublished paper, 1957: "The relation of the Younger Greenstones to the Kurrawang Series at Kundana"). The oblique, apparently cross-cutting Abattoir Line—Cave Rocks Ophiolite Belt, established by both aeromagnetic surveys and ground mapping by geologists of two mining companies, has always seemed to be incompatible with such interpretation, and this objection was strengthened by the recognition of the usual ophiolite belt assemblages—serpentinites, metagabbro sills, pillowed metabasalts etc.—within this belt, suggesting that it is a true ophiolite belt. The anomaly was resolved by McCall (in the press, part 1 of this series of accounts) by means of a revised stratigraphic interpretation (replacing that given in McCall *et al* (1967)), an interpretation which recognised that the Merougil Beds are stratigraphically a long way below the level of the Kurrawang Conglomerates. The Merougil homocline remains the east limb of the Kurawang Syncline extended southwards, but the syncline, though retaining its tight character, has been disrupted by the Yilmia Dislocation, and the corresponding beds on the west side of the structure have been displaced to the south. The northerly plunging structure becomes open immediately to the south of the Merougil Sub-Area, on the east side of the Lefroy Peninsula, where the keel of the syncline has been brought up by the dislocation, on the upthrow side of the fault.

The Merougil Beds are sub-divided as shown in Table 1, and their outcrop is shown in Fig. 2 (folding map). The sequence in the lower part of the succession in the area of good exposure is shown in Fig. 3.

TABLE 1

Succession in the Merougil Creek Sub-Area.

YILMIA DISLOCATION

YILMIA DAM		(Caves Rocks Beds)	
	11,000′	Poorly exposed and kaolinised metasandstones, with some pebble conglomerates.	Merougil Beds
LOWER DAM	4,700′	Metaconglomerates and metasandstones.	
	600′	Fine grained, spotted metasandstones.	
	380′	Sheared metasandstones and metaconglomerates.	
	*60′	Sheared siliceous schists.	

GAP IN EXPOSURE—DISLOCATION

‡(Albite porphyry grading into micro-adamellite porphyry.) ‡(Hornblendic porphyry.) Metabasalts, metagabbros and serpentinites, etc. Pelites, fine cherty metasediments metasandstones.	Red Hill-Kambalda Ophiolite Belt

‡ These are slightly later intrusions, to some extent metamorphised and deformed.

* Braybrooke and Middleton (1964) tentatively equate these with the White Flag (Yindarlgooda) meta-andesites. Re-examination suggests that they are highly sheared metasediments.

Metasediments of the Merougil Creek Sub-Area

1. *Intercalated in the meta-igneous rocks of the Red Hill-Kambalda Ophiolite Belt.*

There are subordinate metasediments intercalated in the greenstones of this belt. As is usual in such belts, fine pelitic slates predominate, but there are also fine cherty sediments and metasandstones. These rocks do not outcrop to any extent in the area.

(a) *Graphitic slates.*

The term "slate" is here used loosely: 52994[1] from the southern tip of the ridge, near the Red Hill Mine, is typical. It forms a thin intercalation between metabasalt and serpentinite. It is a black, slatey rock, packed with pyrite cubes, partly replaced by limonite. In a very fine aggregate of recrystallised quartz and sericite, finely disseminated graphite and accessory tourmaline are also present.

(b) *Fine grained spotted metasandstone.*

53001, from the southern tip of the ridge, near the Red Hill Mine, is typical: a flaggy, brown rock showing faint, dark spots on its surface, it is very similar to the "Fine grained spotted metasandstone" in the Merougil Beds, described below, displaying similar biotite rimmed spots.

[1] Numbers quoted throughout this text refer to the collections of the Geology Department, University of Western Austraia.

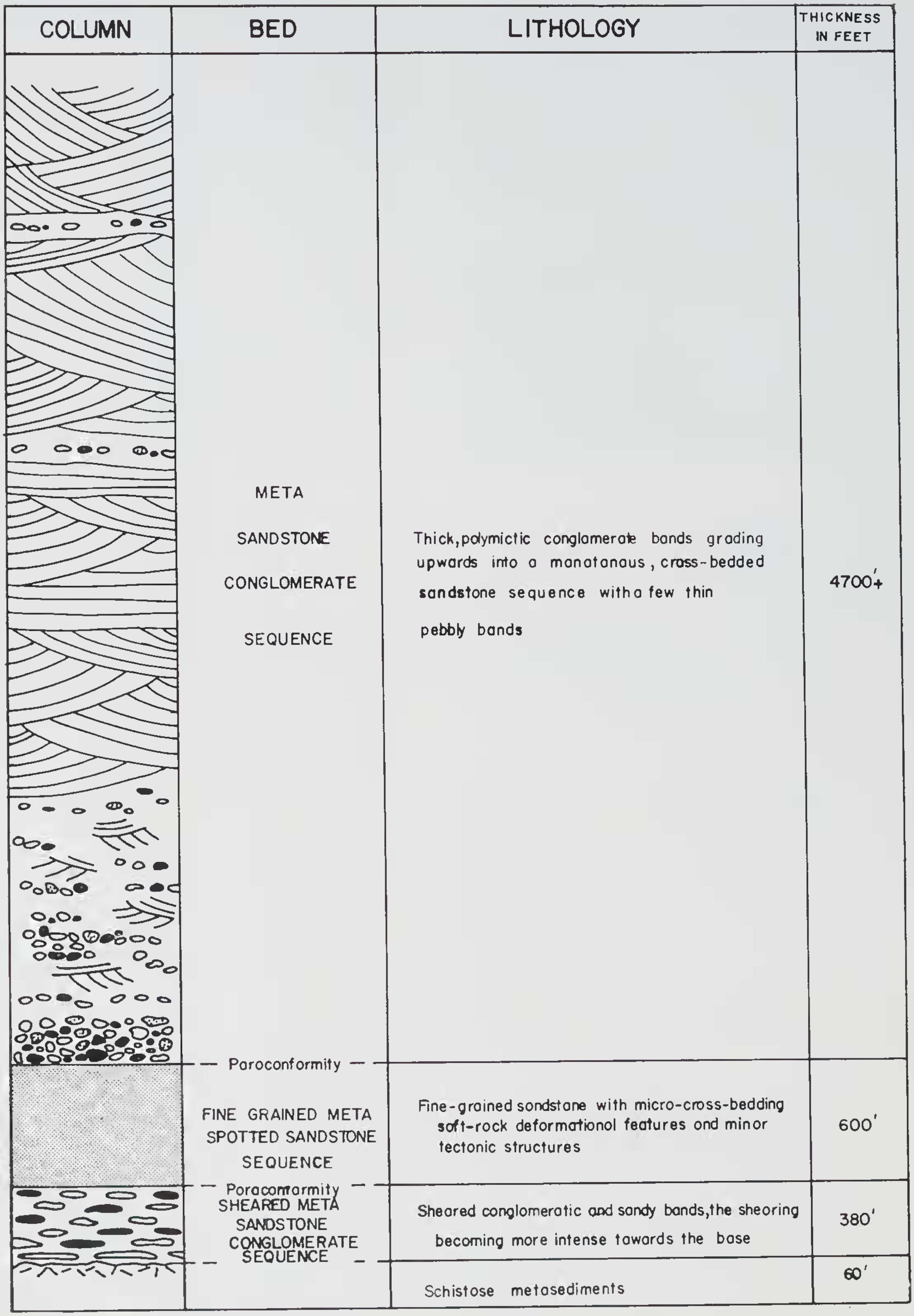


Figure 3.—The stratigraphic column for the well exposed part of the Merougil Beds.

2. *Metasediments of the Merougil Beds.*

(a) *Basal Schistose rocks (60').*

These are only exposed on "Morgan's Island". They are darker and more schistose than the rocks forming the remainder of the Merougil Beds. The low magnesia values revealed on analysis (Table 2) and the lack of modal felspar do not favour the metavolcanic origin suggested by Braybrooke and Middleton (1964) and it seems preferable to regard these as extremely sheared metasediments close to the dislocation. They have lost all trace of primary sedimentary texture. At the base of this unit a gap in exposure intervenes between these metasediments and the porphyry of the peninsula called "Little Italy", and the dislocation is believed to pass through this gap.

A typical specimen, 53033, consists of small, black, parallel-aligned biotite flakes set in a limonitic base. Mineralogically this rock resembles the matrix of the sheared metaconglomerate above it, but the texture is quite different. Small lenses of biotite and flakes of chlorite, together with accessory tourmaline, magnetite and ilmonite, are scattered through a granoblastic groundmass. Biotite (20%), pleochroic from light buff to orange brown or black, occurs as flakes, sinuous trains and poikiloblasts, showing alteration to a paler variety of the same mineral (pleochroic, colourless to yellow). Albite (4%) forms sparse porphyroblasts and minute, parallel aligned, elongated grains, with good crystal form. The magnetite octahedra are commonly biotite rimmed, and there are ghost crystals, the outlines of which are picked out by epidote grains.

53034 differs in that there are discrete lenticles of quartz mosaic, and some calcite and sericite are present. The groundmass, in which a few incipient felspar porphyroblasts are evident, shows evidence of fine crushing and welding (merging of quartz grain outlines). The biotite in this specimen is very coarsely crystallised and associated with intergrown chlorite.

53035 displays a band, 4 mm thick, in which cordierite was surprisingly recognised (Fig. 7), in addition to albite (An_3), chlorite, magnetite, quartz, calcite and muscovite. The cordierite shows sub-rounded outline, and is mostly clear, though some grains show small, parallel sericite ("gigantolite") trains. A few indistinct sector twins are, surprisingly, visible. The optical properties are:—

biaxial +; $2V = 71°$; $N_\beta = 1.547$, corresponding to a composition of $(Mg_{.44}Fe_{1.56})\ Al_4Si_5O_{18}$.

The occurrence seems anomalous: contact metamorphism is the most likely origin, but the igneous intrusion responsible remains obscure.

(b) *Sheared metasandstone metaconglomerates (380').*

The lower metasandstone metaconglomerate sequence consists of an alternation of pebbly metaconglomerate and metasandstone bands, the conglomerates coarsening towards the west (upwards stratigraphically). The contacts with the schists below and spotted metasandstone above are sharply defined. These rocks are characterised by more intense shearing than the rocks stratigraphically above them, but less than the schists beneath them.

A typical specimen, 53013, is sheared pebbly metaconglomerate, in which rounded granules (AGI Dictionary of Geological Terms, 1962, p. 217, entry no. 1), pebbles and cobbles of contrasting lithology are evident. Rocks of acid porphyry appearance (but possibly either igneous or metasomatic origin) predominate amongst the phenoclasts, which are set in a sandy matrix rich in secondary calcite. The calcite is commonly aggregated in limonite stained patches. The sandy matrix consists of a quartz-sericite aggregate, including some small, elongated albite (An_6) grains. Albite and quartz porphyroblasts, in various stages of development, and some ghost porphyroblasts (invisible under crossed nicols) are set in the matrix. Quartzite phenoclasts are also present, some showing fine colloform patterns of dust lines suggesting chert. Accessories in the matrix are tourmaline, epidote and magnetite. The quartz grains show a merging of their outlines, a welding effect producing small patches of quartz porphyroblasts.

In 53014, a sheared pebbly metaconglomerate, the outlines of the pebbles are somewhat indistinct in hand specimen, although some irregular metasedimentary and porphyroid pebbles are visible. The pebble outlines are extremely difficult to locate in thin section. 53020, another sheared pebbly metaconglomerate, differs in the degree of elongation and flattening of the originally rounded phenoclasts. The matrix is granoblastic, consisting of quartz and sericite. The texture is locally so drawn out that it comes to resemble that of a micaceous schist, with bifurcation and anastomosing of the schistose matrix around pebbles and less sheared areas of the matrix. The pebbles in this metaconglomerate show neck like constrictions (p. 30).

Cataclasis increases in this stratigraphic unit down dip, that is towards the west. Shearing was manifestly selective, certain bands being highly sheared, others remaining undeformed. Shearing in the matrix is also inhomogeneously distributed. Both metamorphism and a form of metasomatism, tending towards the production of a homogeneous rock from a heterogeneous parent, seem to have operated (p. 26).

(c) *Fine-grained, spotted metasandstones (600', lensing out southwards).*

Sharp contacts bound these rocks above and below. They are characterised by micro-cross bedding, ripple-marks, soft rock deformations including ball and pillow structures; and all these give a consistent west facing. The only megascopic tectonic structures, besides joints, seen in the Merougil Beds are fracture cleavage and small scale folding restricted to fine-grained layers in this unit.

A typical speciment is 53996, a fine-grained metasandstone: a dense, dark grey, micro-cross bedded rock. It is traversed by thin veinlets of quartz and associated hematite. A fine-grained quartz-sericite groundmass encloses porphyroblasts ($\leqslant$ .15 mm diameter) and scattered flakes of biotite (yellow-red brown), commonly associated with muscovite. The biotite is altered to magnetite and prochlorite, while calcite is also sparingly present as granoblastic grains and narrow veinlets. Anhedral magnetite (and hematite after it), epidote, tourmaline (var. schorl) and apatite are accessories present.

There is much evidence of progressive recrystallisation having occurred with increased shearing stress in these rocks, biotite progressively adopting a more perfectly parallel flake orientation, and other minerals tending to form an even, granoblastic aggregate which shows a concordant grain elongation. The progression is from the *semi-schist* texture to a true *schist* texture (Figs. 8 and 9). Spotting in rocks of this sequence ranges from quartz cored aggregates of biotite flakes to quartz cored single biotite flakes and single biotite flakes without a quartz core. Outlines are diamond shaped, hexagonal or rounded, and limonitic replacement is common. The origin of the spotting is discussed under metasomatism.

Micro-cross bedding is evident in 53043, the biotite flakes within the foreset beds also forming an internal grading; flakes 0.1 mm long at the bottom grading upwards into progressively smaller dimensions, the upper part of the graded unit being quite free of biotite (Fig. 40). The structure is unusual because elsewhere in the Kalgoorlie system biotite grades show an increase in size and content of biotite flakes in the reverse direction (Dunbar, 1966).

(d) *Metaconglomerate and metasandstone (4700').*

The upper limit of this subdivision is arbitrarily drawn at the limit of good exposure near the lower dam on Merougil Creek. By far the thickest metaconglomeratic unit within the

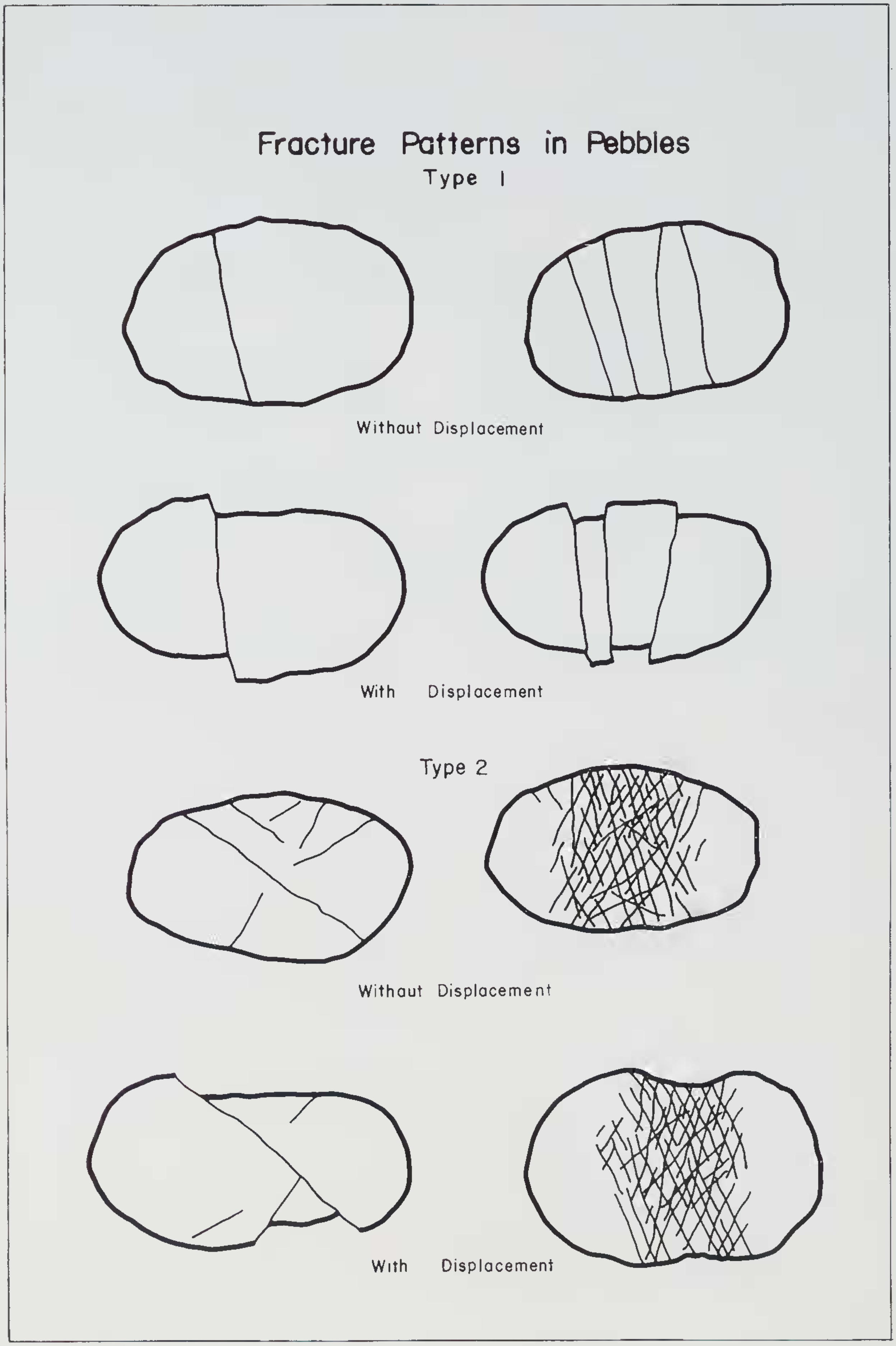


Figure 4.—Line diagram showing the two types of fracturing of the pebbles.

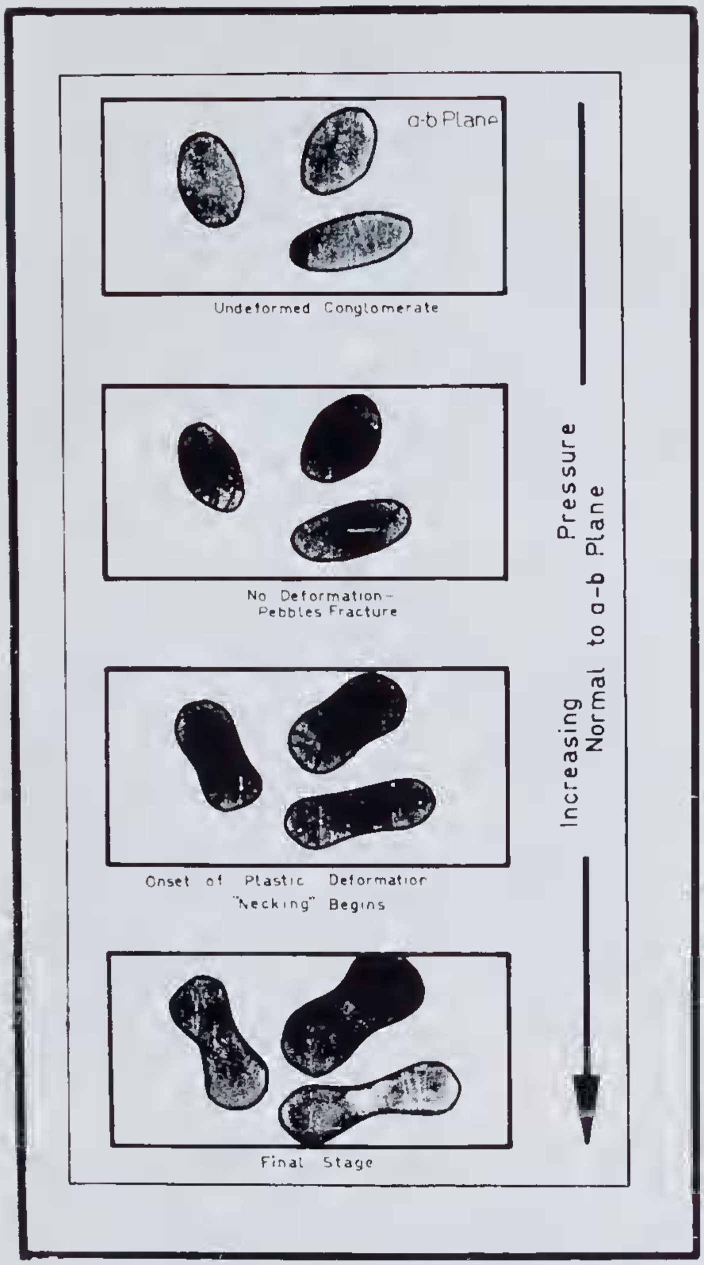


Figure 5.—Line diagram showing the mode of origin of dumbbell forms in deformed pebbles.

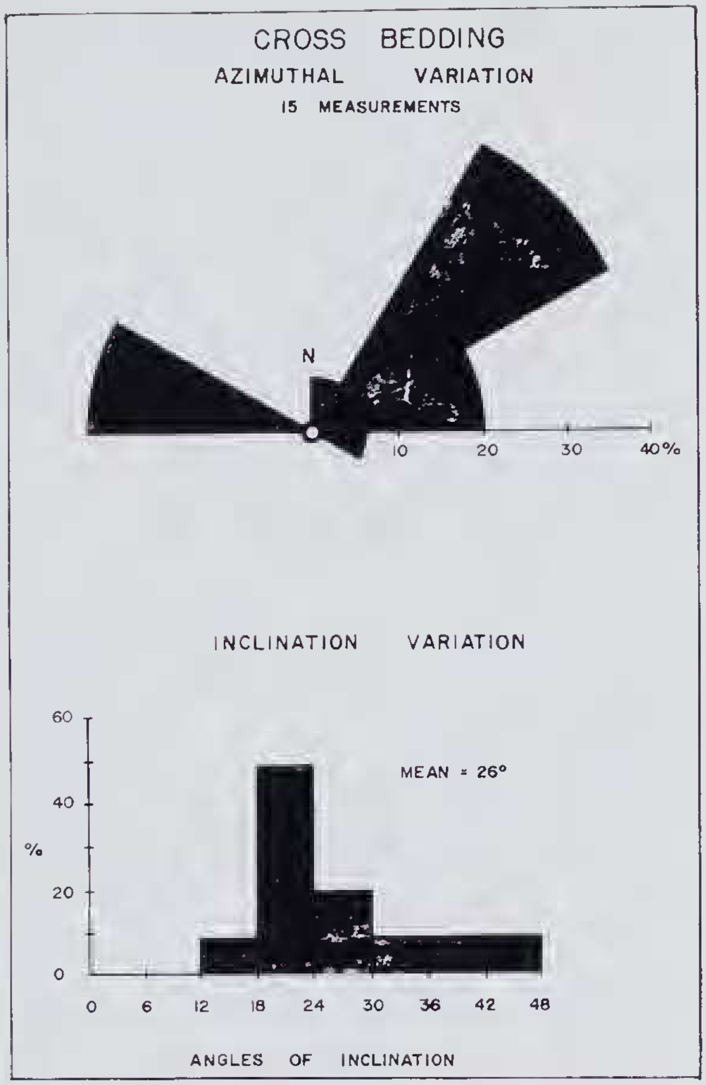


Figure 6.—Current-rose for the Merougil Creek sub-area.

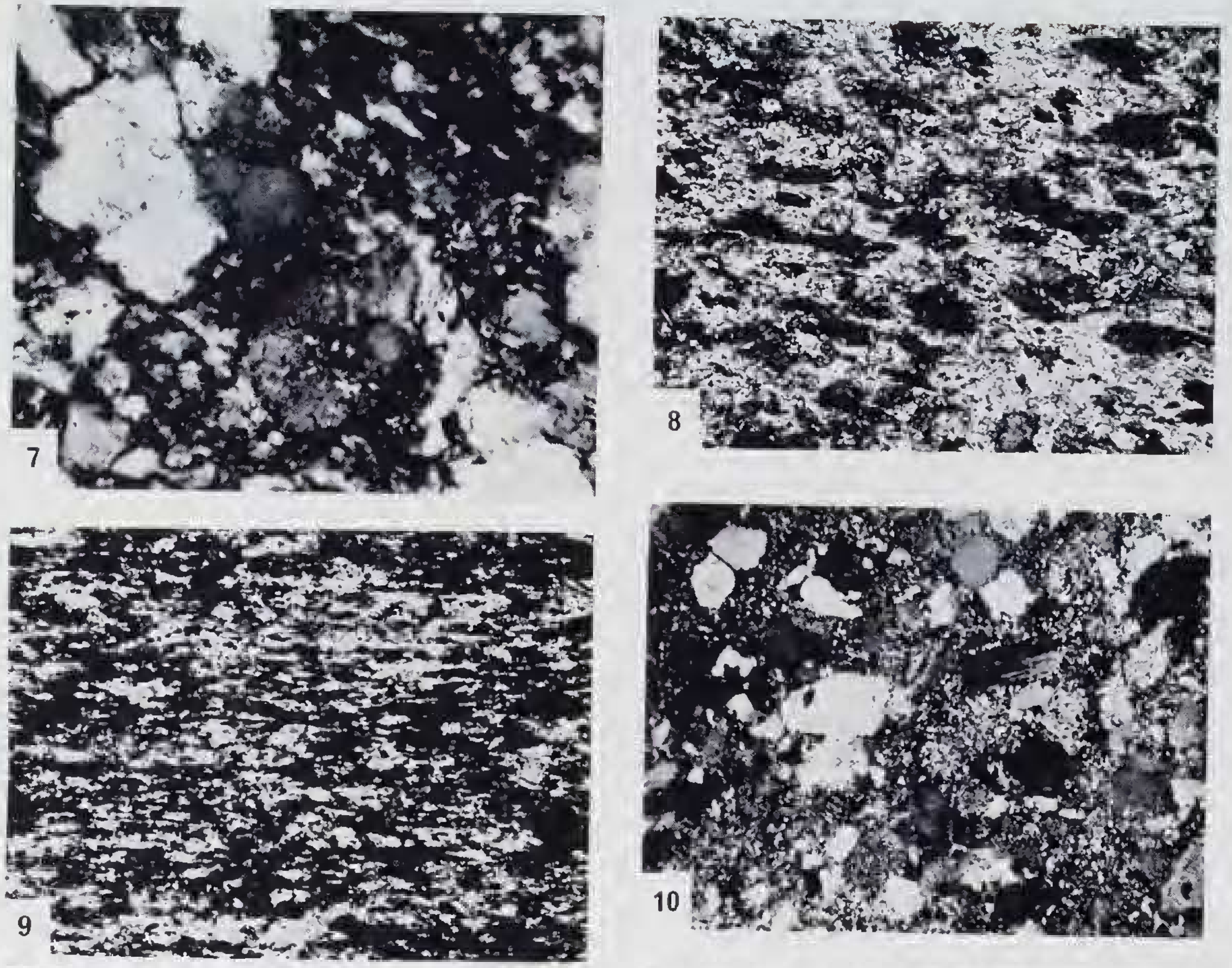
Merougil Beds, this consists mainly of polymictic metaconglomerates composed of rounded pebbles, cobbles and boulders set in a metasandstone matrix, which commonly displays cross-bedding in coarse festoons. Metasandstone also forms intercalations in the metaconglomerate, and there is a gradual passage upwards, stratigraphically, into a monotonous sequence of metasandstone, relieved only by a few thin pebbly bands.

A typical specimen of the metastandstone is 53004, a dark-grey, dense, medium-grained rock with a typical semichist texture (Fig. 10). Large, medium-sized and small-sized grains of quartz and felspar, mosaics of quartz, and biotite flakes, are set in a finely granoblastic matrix. In larger grains, grain boundaries tend to merge with the matrix. Many grains are fractured and healed by granoblastic quartz. The quartz mosaics represent a stage in the homogenisation; various degrees of mergence of the large grains with the granoblastic groundmass can be seen (Figs. 13 to 16). Albite is present as euhedral to anhedral grains showing albite and Carlsbad twinning. Larger grains show strain effects. Many grains are partly altered to sericite. Biotite flakes (buff; red-brown) occur as clots, small individual flakes and poikiloblastic plates. They rim quartz and felspar crystals and are altered to magnetite and chlorite. Calcite of secondary origin is scattered throughout the rock. The groundmass is a fine granoblastic aggregate of quartz and a little albite shot through with sericite flakes.

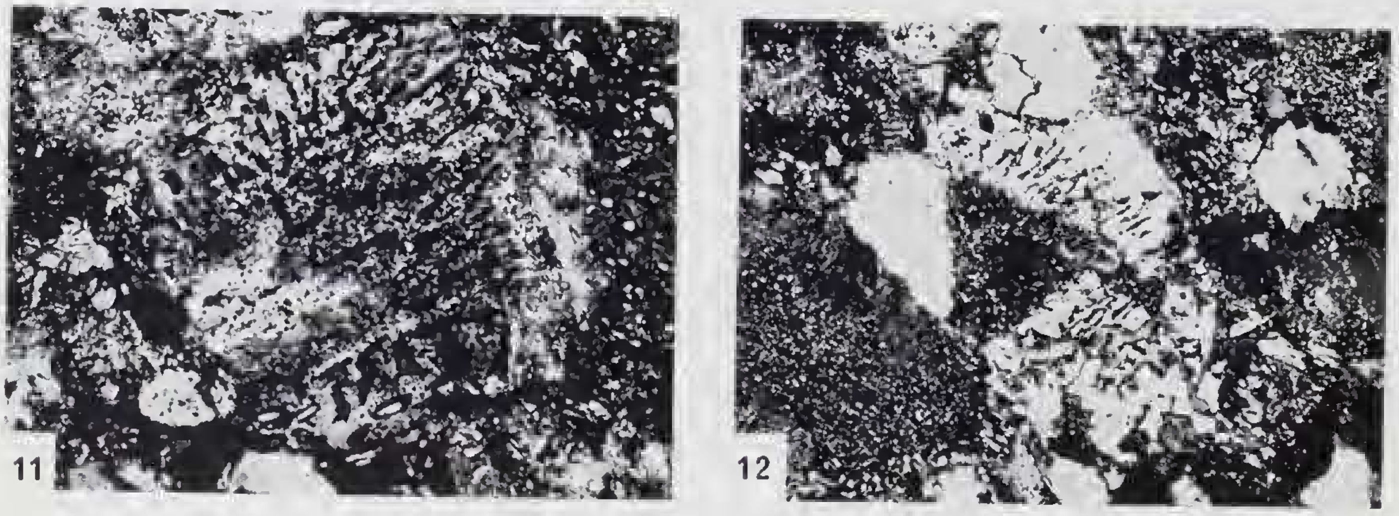
In other similar rocks there are patterns of albite-quartz replacement intergrowth, commonly vermiform: also radiating net-works of secondary silica surround some grains (Figs. 11 and 12). Zircon (rounded off euhedra), apatite and tourmaline (schorl) are acessories. These rocks show evidence of selective granulation of the quartz grains, dependent on the favourability of grain orientation to shearing stress (Fellows 1943, p. 1416). The quartz and albite show a cloudy dusting of dark particles at the centre and cleared rims (Fig. 10) (see Poldervaart and Gilkey, 1954 for a discussion of the origin of this phenomenon).

53005, an albitic metasandstone, is a dark grey, dense, medium grained rock containing more albite than 53004, as well as muscovite poikiloblasts, and chlorite-biotite intergrowths. There is a gradation from shapeless felspar grains showing some clear-cut faces, as well as some indistinct boundaries to euhedral grains with only clear-cut boundaries (Figs. 17 and 18). The biotite shows evidence of metamorphic retrogressions to prochlorite.

53006 is typical of the metaconglomerate matrix, being a dense dark-grey, medium-grained metasandstone, with thin bands of biotite-rich material parallel to the bedding. It consists of recrystallised quartz grains ($\leq$ 3 mm) set in a fine grained quartz-sericite groundmass. The matrix shows less shearing effects than the metasandstone layers, probably because of the *pressure shadow effect* of the pebbles. It is otherwise very similar to 53004. Secondary calcite and tourmaline may be present, the latter mineral as discrete needles and small "suns". It is notable that the pebbles are very similar



Figures. 7-10.—Microtextures of metasediments.—7. Cordierite crystals in specimen 53035 (crossed nicols, X200). 8. Texture of a metasiltstone: biotite flakes and small porphyroblasts set in an irregular base of quartz and felspar grains (52996) (Plane polarised light, crossed niçols, X63). 9. Schistose texture of an extremely sheared metasiltstone (52998), in which the biotite is set in a drawn out, granoblastic, quartzose mosaic. (Plane polarised light, crossed nicols X100). 10. Texture of a metagreywacke (53004): large medium sized, and quite small quartz and felspar grains are cemented by a fine, granoblastic quartzose matrix. The large grains have had their clastic outline modified and the fine groundmass shows no trace of clastic texture. (Crossed nicols X63).



Figures 11, 12.—Secondary silicification of albite.—11. Twinned albite grain showing secondary silicification (53038) (crossed nicols X160). 12. Network of secondary silica around the vestigial remains of a felspar grain (53012) (crossed nicols X63).

to the enclosing sandstones and could be locally derived (but see discussion, (p. 23). 53008 is a metaconglomerate consisting of pebbles up to 5 cms diameter, moderately well rounded, and of varying size and lithology. Fine-grained metasandstone and "porphyroid" pebbles predominate. Some of the quartz grains in the matrix show straight crystal faces and appear to be porphyroblasts. There is considerable apatite in the form of needles included in the quartz grains, suggesting granite provenance.

Description of the conglomerate pebbles.

These are easily extracted from the matrix of the main conglomerate; though not from the sheared conglomerate, in which the boundaries of pebbles have been welded into the matrix, and show only traces of polymictic character, having been largely homogenised, so that study of this unit is not at all rewarding, except in respect of metamorphism and metasomatism. On the other hand, the main conglomerate unit provides pebble material which retains the original sedimentary or ingenous texture to a considerable degree.

250 pebbles were examined from 3 localities and 57 were selected for thin section study. There is no observable variation in the proportional representation of any particular rock type from locality to locality. The pebbles may be divided into three types:—

(a) Porphyroid pebbles (predominantly derived from igneous porphyries).

(b) Granitic pebbles.

(c) Metasedimentary pebbles.

(a) Porphyroid (mostly "porphyry") pebbles.

These have been arbitrarily divided into four sub-groups on mineralogical and textural criteria.

Type I. These show large rhomb-shaped or stoutly rectangular albite megacrysts * (≤ 10 mm). There are no quartz megacrysts. In this group only two pebbles are included: a typical specimen is 53051 (Figs. 19 and 21) which shows plagioclase (An_{10}) with twinning rarely evident, and slight alterations to kaolin and sericite. Inclusions are quartz, muscovite calcite and chlorite. The quartz inclusions are irregular, appearing like intergrowths. There are felspar inclusions within the felspar (not in optical continuity with the host-K-felspar? (2V ± 80°). The quartz in the very fine groundmass is lobate and sutured producing a dense, interlocking aggregate. There are some large, granoblastic "compound" areas made up of as many as fifty component grains—these seem to stem from recrystallisation of the groundmass and not to be recrystallised megacrysts.

Biotite (pale yellow brown/dark brown) occurs as ragged plates and flakes (≤ 1 mm), commonly aggregated in clusters, and is partly altered to chlorite. The texture is porphyritic, euhedral, megacrysts being set in a fine allotriomorphic groundmass. There seems little doubt that this is a porphyry of magmatic origin, modified by metamorphism and metasomatism. 53052 provides more evidence for magmatic origin since the sericite alteration product picks out the concentric zones of the original more calcic plagioclase (Fig. 22). It also contains some tourmaline (schorl).

These pebbles were probably derived from intrusive acid porphyries containing both K-felspar and plagioclase phenocrysts.

Type II. These show well formed but rare albite and smaller quartz megacrysts. About one-fifth of the porphyroid pebbles examined fall into this category. A typical specimen is 53053, which shows megacrysts of clear, white quartz, together with larger, and more sparse megacrysts of opaque, white plagioclase, set in a dense, dark grey, porcellainous groundmass. The quartz (3 mm-1 mm) is present as six-sided euhedra grading down to quite anhedral grains. The grains show some embayed margins (Fig. 20) and groundmass inclusions (p. 22): also some indistinct, merging margins. The groundmass shows some recrystallised areas, which form patches of the same size as the megacrysts. Albite (An_8) ranges from 0.4 to 5 mm in maximum dimensions: albite and Carlsbad twinning are well developed, and there is some sign of alteration. Biotite flakes (0.2-1 mm) show ragged outlines. They also show partial conversion to chlorite.

Apatite is included in the plagioclase. There is also some calcite, epidote and pyrite present in the felspar grains. The groundmass is a fine-grained aggregate of quartz and minor plagioclase showing some recrystallisation and welding of grains to larger individuals. Other specimens reveal numerous fresh, well-formed plagioclase grains, which are believed to be metasomatically derived, by recrystallisation.

Type III. These show abundant biotite, occurring as inclusions within the albite megacrysts: Such pebbles make up more than two-thirds of the total number of porphyroid pebbles studied. A typical example is 53055 which shows abundant biotite at the borders of subhedral albite megacrysts (Fig. 23). The albite grains (An_8), range from 0.5 to 3.5 mm diameter. The inclusions are commonly present along the cleavage direction or the composition planes of albite twins, as well as being irregularly aggregated on the grain boundaries. Calcite, epidote, apatite and pyrite are also included. The felspar shows some albite and Carlsbad twinning—also rare pericline twinning. Quartz is present as anhedral, rounded to crudely dipyramidal phenocrysts (≤ 1.5 mm) and minute anhedral grains (± 0.3 mm) in a very fine groundmass. The larger quartz grains show embayments and inclusions of the groundmass. Biotite also is present in the groundmass, as well as chlorite, magnetite pyrite, apatite and calcite, together with very small grains of untwinned albite. The biotite inclusions may have developed during cooling of a magma: they may represent basic material expelled from felspar growing in a solid state: or they may represent material crystallised in phenocrysts long after their formation, during metsomatic modification. The last explanation is preferred (see discussion, p. 22).

53056 shows both an irregular scatter of biotite flakes included in the felspar as well as concentration at the core and not at the rim. There is much more biotite in the groundmass, occurring as patches which seem to represent incipient porphyroblast growth. Quartz megacrysts (anhedral to crudely dipyramidal) and patches of granoblastic quartz of varying individual grain orientation after megacrysts are also present (Fig. 24).

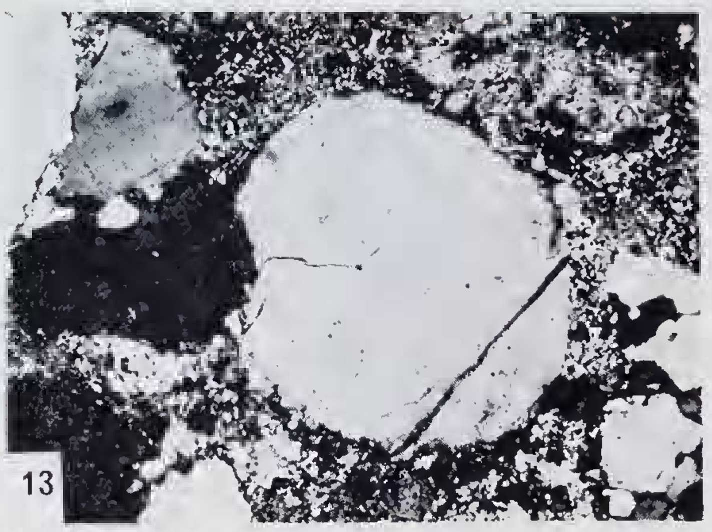
Type IV. These are characterised by a groundmass different from that of the other three types, which show similar groundmass characteristics.

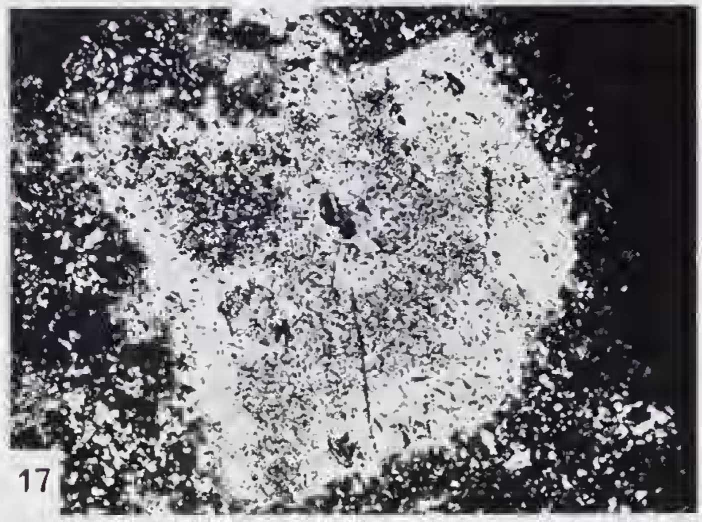
About 5% of the porphyroid pebbles studied were of this type. 53059 is typical, showing subhedral to euhedral albite (An_7) (≤ 6.0 mm) and quartz (≤ 3.0 mm) megacrysts, a few showing dipyramidal forms, set in a dense medium grey, allotriomorphic/hypidiomorphic-granular groundmass. The albite shows albite and Carlsbad twinning in most grains. Both quartz and albite megacrysts are embayed; the latter has inclusions of groundmass, and a few biotite flakes along cleavage planes. The biotite is also present as sparse plates and flakes (≤ 0.8 mm). Apatite and pyrite occur as inclusions in the groundmass which is much coarser than in any of the pebble types so far described, and consists of subhedral plagioclase, anhedral quartz (± 0.3 mm), and biotite flakes. The quartz and biotite are quite distinctly interstitial to the plagioclase (Fig. 30), and there is no complex suturing of grain margins, though the quartz-felspar interface is commonly marked by an intergrowth zone.

The texture, here and there, tends to be glomeroporphyritic.

These four types seem to represent a related set of magmatic porphyry rocks (mainly quartz porphyries): however, the evidence for magmatic origin in the case of Types II, III and IV is by no means so clear-cut as it is in the case of Type I (see further discussion of metasomatic modification (p. 20).

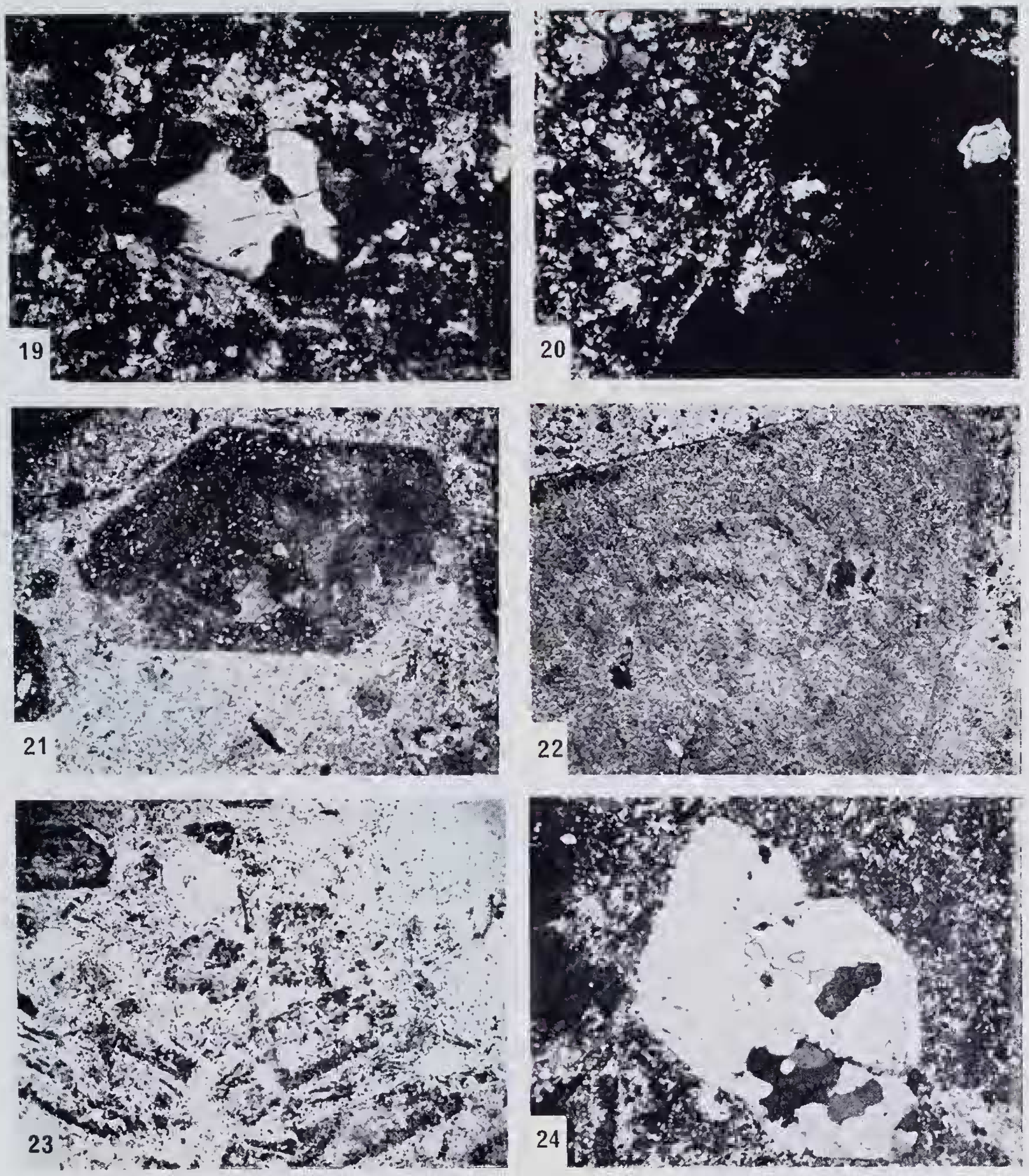
* All large grains in the fine groundmass are here referred to as megacrysts—for, although some may be phenocrysts and others porphyroblasts, it is impossible to distinguish one from the other.





Figures 13-16.—Stages in the granulation of quartz fragments in meta-greywackes.—13. Rounded grain quartz, only slightly fractured and not granulated (53044) (crossed nicols X63); smaller grains nearby show incipient granulation. 14. Grain entirely granulated to an even mosaic (53012) (crossed nicols X63). 15. Relict quartz grain, very finely granulated and outlines indistinct (53012) (crossed nicols X63). 16. Relict quartz grain, outlines almost entirely obliterated and difficult to distinguish from the finely granoblastic matrix; the finely granulated quartz has suffered incipient welding together of the component granules (53089) (crossed nicols X160).

Figures 17 and 18.—Final stages of albite growth in metasandstone and metasiltstones.—17. Subhedral albite porphyroblast showing both good and irregular, merging crystal faces, and also partial clearing of sericite and biotite inclusions in the marginal zone (53005) (crossed nicols X63). 18. Clear, euhedral albite porphyroblast (53008) (crossed nicols X 25).



Figures 19-25.—Acid igneous rock (?) pebbles in metaconglomerate.—19. Porphyroid inclusion (53051) showing a quartz aggregate (recrystallised megacryst ?) with a deep groundmass filled embayment (crossed nicols X160). 20. A similar embayment (53053): a quartz megacryst extinguished, shows an indistinct margin merging with the groundmass (crossed nicols X160). 21. Albite megacryst showing an approach to the characteristic form of rhomb-porphyries, both merging and clear-cut faces, and a faint incipient granulation within the crystal (53051) (crossed nicols X10). 22. Albite megacryst preserving relict zoning (53052) crossed nicols X25). 23. Biotite concentrations in plagioclase megacrysts (53055) (plane polarised light, X10). 24. Quartz megacryst showing conversion to an granoblastic mosaic with sutured boundaries (53056) (crossed nicols X25).

(b) *Granitic Pebbles*

These account for about one quarter of all pebbles studied (c.60). They are commonly larger than other pebbles (up to 9″ diameter), and are of very uniform character.

53061 is a medium-grained biotite granodiorite with prominent pale subhedral plagioclase crystals ($\leqslant$ 4.0 mm), and biotite flakes. The plagioclase is euhedral, intergrown with quartz (Fig. 25), and commonly shows albite and Carlsbad twinning with pericline twinning less common. Inclusions of biotite and rare chlorite are present, and patches show alteration to sericite and kaolin. Quartz is present as anhedral grains ($\leqslant$ 2.0 mm) and in micrographic intergrowths; biotite as ragged flakes (yellow: dark brown): chlorite, epidote magnetite and apatite are also present. The feldspar in the graphic intergrowths (commonly interstitial) may originaly have been K-felspar, subsequently converted to albite during metamorphism. The texture is hypidiomorphic granular. 53062 shows distinct zoning in the plagioclase, picking out by alteration products. The quartz-felspar intergrowth is less abundant (? a less potassic granodiorite). However, in the case of 53063, the quartz-felspar intergrowths are unusually abundant and, assuming the intergrown felspar was originally K-felspar the rock must have been an adamellite. 53064 is an aplite pebble, composed of a sugary plagioclase (An_{13})—quartz intergrowth.

(c) *Metasedimentary pebbles.*

Approximately half the pebbles studied were metasedimentary.

53065, a fine to medium-grained albite-quartz-biotite metasediment, is typical. It is a dark grey massive rock showing numerous greenish-brown biotite flakes in hand specimen. The biotite is yellow to dark brown in thin section, and its properties suggest about equal magnesium and iron content. The flakes tend to be clustered in irregular patches, and include epidote, apatite and quartz. Quartz forms anhedral grains in the groundmass ($\leqslant$ 0.2 mm), commonly showing outgrowths and fusion of boundaries. Albite occurs as fresh, anhedral, untwinned, poorly cleaved grains of the same size. Penninite, epidote, calcite and apatite are all present. The texture is one of decussate biotite flakes set in an allotriomorphic, granoblastic groundmass of quartz and felspar (Fig. 26). Another pebble only differs in the presence of small rounded porphyroblasts of albite (An_9) containing biotite inclusions, and limonite pseudomorphs after pyrite cubes. This pebble type appears to be a metamorphic derivative of a fine-grained argillaceous sandstone or siltstone.

53068 is of less biotitic character—a dark grey, massive, fine-grained metasediment with biotite showing as discrete, equidimensional flakes in hand specimen. Again, anhedral quartz ($\leqslant$ 0.05 mm) and fresh, anhedral grains of untwinned albite make up the groundmass (Fig. 27), which also contains some apatite, pyrite and calcite. 53071 displays a maculose texture produced by clustered biotite porphyroblasts. These rocks seem to be metamorphic derivatives of less argillaceous sandstones and siltstones.

Metasedimentary pebbles with no biotite are rare, but tend to be conspicuous, showing white on metaconglomerate surfaces. 53072, a metaquartzite, is typical. It is composed of a granoblastic aggregate of quartz grains together with interstitial epidote (Fig. 28). Specimen, 53074, (Fig. 29), is a fine-grained chert, made up of a very fine aggregate of lobate and completely sutured quartz ($\leqslant$ 0.3 mm).

Provenance of the pebbles

During their history the pebbles have been—

(a) separated from their parent rock mass

(b) transported to the site of deposition of the conglomerate

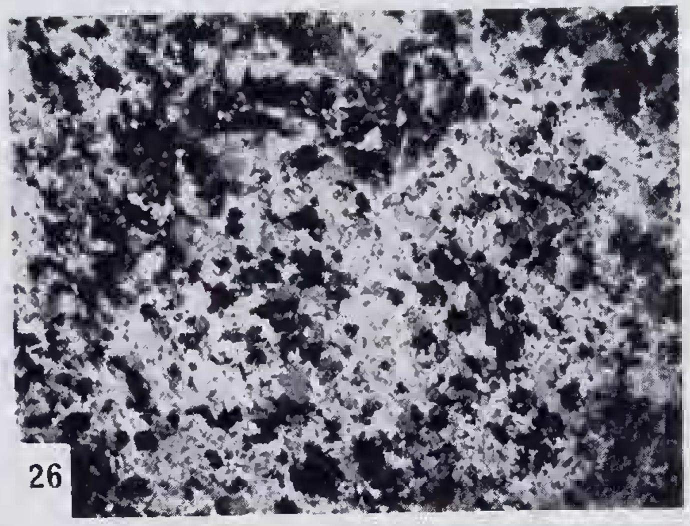
(c) regionally metamorphosed (and metasomatised in some cases).

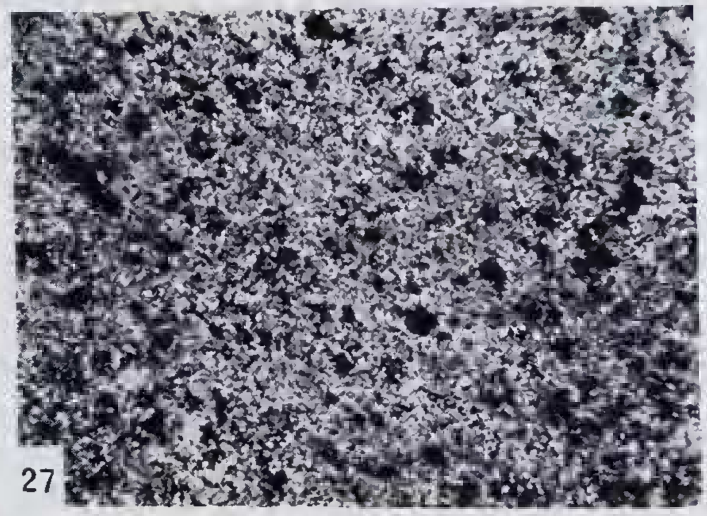
This is the simplest possible history, but stages in this cycle may have been repeated more than once. The igneous origin of some pebbles cannot be denied (evidence of relict zoning: granite pebbles). Some metasedimentary pebbles show isolated felspar porphyroblasts, indicating that some of the porphyroid pebbles may be of sedimentary origin, altered by metasomatism or metamorphism *while incorporated in the conglomerate*. However, the great variety in style and degree of large crystal development from one pebble to another, and between pebble and matrix, suggests that the origin of most large crystals is by crystallisation *before incorporation in the conglomerate*, and that since then they have been modified and some new porphyroblasts have been added to pebbles and matrix. Indeed, it is difficult to envisage a process whereby such heterogencity of porphyroblast development could develop in a conglomerate, all parts of which, in the case of a restricted outcrop must have suffered an identical metamorphic history after aggregation. Yet, if there is any truth in the concept of *porphyroid metasomatism* (the mechanical and metasomatic transformation of rudites and psammites to porphyry-like, more homogeneous rocks within a low-grade metamorphic environment) we must bear in mind the possibility that such a pattern of heterogencity *could develop* in a conglomerate made up of porphyroid rather than porphyry pebbles—i.e. of rock fragments derived from an earlier episode of porphyroid metasomatism, similar to that recognised in the Lake Lefroy area and discussed below on p. 25 and later in this series of accounts. Only in the very few cases of zoned crystals and in the case of granite inclusions have we really firm evidence of magmatic origin for the pebble material, but in spite of this, it is believed that the pebbles are mostly of magmatic origin, though the texture of the felspars in these porphyroid pebbles indicates a complex metasomatic history: for example:—

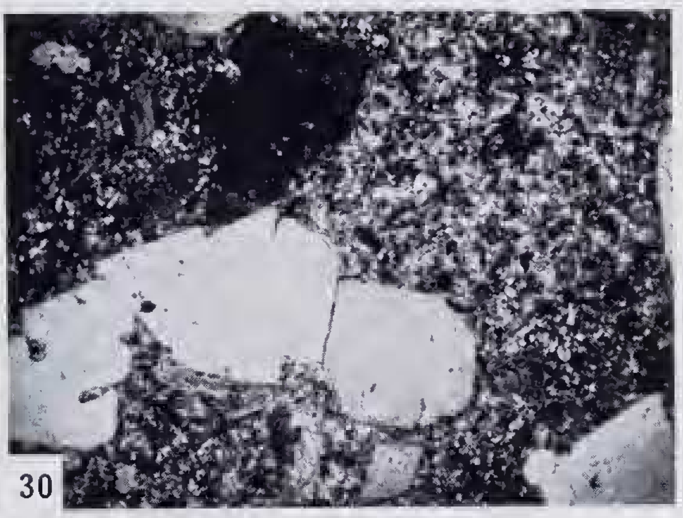
- chess-board albite—replacement of original K-felspar by albite (Anderson, 1937, p. 62-3).
- quartz intergrowths and mica flakes as inclusions—also likely to indicate replacement of an original K-felspar (liberation of excess SiO_2—Anderson, 1937, p. 28).
- zoning (palimpsest)—replacement of an earlier, more calcic, magmatic felspar by albite.
- biotite inclusion (sometimes marginal)—suggests expulsion of material from growing porphyroblasts (Goodspeed, 1937, p. 1136).

Biotite is, however, two to four times as abundantly included in the felspars, as in the groundmass, and groundmass minerals are seldom observed as inclusions in the biotite. On the other hand, such large volumes of biotite, selectively included in *phenocrysts* of albite, are difficult to accept; indeed such textures are simply not typical of albite and quartz porphyry types of igneous rocks. Poldervaart and Gilkey (1954) have discussed the migration of iron down concentration gradients:—

> "Given a sufficiently high temperature level for diffusion, ions could migrate down concentration gradients; temperature probably also governs which particular ions are predominant in a solution at any particular time. Iron apparently migrates at rather low temperatures. With an adequate tem-







25. Granitic pebble (53061), with subhedral albite (dusty grey) and interstitial micropegmatite (crossed nicols X25).

Figures 26-29.—Metasedimentary pebbles in metaconglomerate.—26. Biotite-rich metasediment (53065): biotite, dark; quartz, white; albite, grey (plane polarised light, crossed nicols X25). 27. Finer biotite metasediment (53068) (crossed nicols X25). 28. Quartzite (53072) (crossed nicols X10). 29. Chert (53074) (crossed nicols X10).

Figures 30-31.—Comparison: dipyramidal quartz.—30. Porphyroid pebble (Type IV) (53059): showing crudely dipyramidal quartz phenocrysts (?) with marginal embayments, set in a matrix of anhedral quartz and subhedral albite (crossed nicols X10).

perature level, sufficient time and the presence of water, a fluid phase rich in iron will be developed in rocks. In any plagioclase crystal, iron concentration along the internal phase boundaries and any other surfaces of greater separation (cleavage, twin composition planes) will be lower than in the surrounding pore fluid, hence iron will tend to migrate along these potential passages into the crystal and will go on doing so until some degree of equilibrium is maintained. Other ions will also tend to establish equilibrium by migration into and out of crystals. With a subsequent decrease in temperature, iron will be crystallised from the pore fluid, perhaps as magnetite. At the same time magnetite will crystallise from iron present along internal phase boundaries since there is equilibrium. Similarly, hematite, spinel, garnet, biotite, rutile, hornblende, all these may form inside the crystal at the time when it is being crystallised from the pore fluid'.'

This statement is quoted in full because it allowed for the possibility that the biotite within the plagioclase phenocrysts has originated in just this way. Sufficient heat could come from the nearby intrusive porphyry (p. 25) and there is ample evidence of fluid movement during metamosphism. *But the excessive concentration of biotite in the felspars is still not explained,* for the theory requires *equilibrium between matrix and phenocryst,* and *at the most, equal concentrations should be obtained.* Rapid removal of pore fluid by migration out into the sedimentary matrix of the conglomerate after the attainment of equilibrium and while the component ions were still in solution could explain this anomaly, but such a removal would have to be at a rate that inhibits continual readjustment of concentration to an even level, and so leaving the greater part of the biotite inside the phenocrysts and only depleting the groundmass of the pebble. This does seem a rather delicately controlled mechanism, but it is the best answer so far suggested, and though there can be no definite conclusion concerning the process which occurred during metamorphism and metasomatism of the conglomerate, something on the lines given above does seem the most likely answer to the strange relationships observed. The conclusion that can be drawn is that the biotite inclusions are almost certainly late, metasomatic, and have no significance at all with regard to the ultimate origin of the porphyroid pebbles, which may in spite of their strange present appearance, be magmatic (i.e. a porphyry) or metasomatic (i.e. a porphyroid derivative of a metasediment from an earlier depositional sequence, metasomatised during an earlier [pre-Kalgoorlie System] metamorphism).

Other possible criteria for *porphyroblastic* or *phenocrystic* origin of felspars appear ambiguous. The most obvious are mineral/groundmass relationships. Groundmass relics have been considered by Misch (1949) and Goodspeed (1937b) to be indicative of porphyroblastic origin, and there certainly is some evidence here of such structures, and of porphyroblastic growth: however, most if not all of the relationships observed could be attributed to metasomatic outgrowth of original phenocrysts. Crystal shape is certainly no criterion (Davey, 1934), for rounding of outlines may be due to either magmatic resorption or porphyroblastic growth in a resistant medium. The quartz crystals certainly show euhedral forms, with pyramid faces dominant (Fig. 27), which could be argued as indicative of the high-temperature β-form commonly developed in intrusive quartz porphyries (being first developed and later reverted to the low temperature form). However, the pyramid face may develop to a greater extent than the prism in *metamorphic growth,* as has been shown by Misch (1949, p. 388). Similarly, deep groundmass-filled embayments may be due to *magmatic resorption,* though it is very difficult to imagine a quartz-rich residual melt resorbing quartz phenocrysts which should be stable in it, and the narrow embayment form seen in these examples seems unlikely to develop during resorption which should operate on a wider front. So there is evidence favouring *porphyroblastic* origin for many of the quartz megacrusts, and to a lesser extent for the ablite megacrusts. The presence of diffuse margins to the quartz megacrusts near embayments supports this view (Misch, 1949 p. 389).

Bradley, (1956, p. 177-9) attributes embayments to solution of strained parts of quartz crystals: where growth and resorption occur simultaneously, the neck of the embayment tends to close. This concept is readily applicable to the Merougil rocks which have manifestly been highly stressed, but it also suggests that an origin in phenocrystic crystallisation in a magmatic porphyry, and modification by later embayment, solution and recrystallisation, during the period of stress associated with the regional metamorphism of the conglomerate is quite tenable.

The groundmass provides no clue, being recrystallised so extensively that its original texture is obliterated.

From the evidence available the authors can only conclude that the criteria of magmatic or metasomatic origin for the porphyroid pebbles eludes them While a few can be firmly recognised as meta-igneous pebbles (e.g. Fig. 22), the majority are too modified by metamorphism and metasomatism within the conglomerate to be firmly identified as of one or the other origin.

The porphyroid pebbles are not unlike similar rocks which are numbered among the more common rock types of the Kalgoorlie system—the *albite* and *quartz porphyries.* No correlation can, however, be made with any known occurrence sharing some characteristic and unusual textural or mineralogical feature, and indeed local provenance remains unlikely. Consideration of the probable palaeogeography (p. 29) suggests that pebbles in this conglomerate deposited at the border of a geosynclinal furrow would have come from a raised land mass further to the west; and from nowhere near the Kalgoorlie systems' present outcrop. Studies by Glikson (Thesis, 1968), of the Kurrawang conglimerate pebbles, suggest that the porphyry material included as pebbles is, in part at least, exotic, not locally derived. It is probable that these similar porphyroid rock types were a common feature of early Precambrian metamorphic sequences, and that the pebbles are products of an earlier "pre-Kalgoorlie" metamorphic / intrusive / metasomatic event.* That the "porphyroid" pebbles of the Merougil metaconglomerates and magmatic porphyry pebbles is the much simpler answer, and, largely intuitively, it is favoured.

The granitic pebbles strangely, have not been greatly modified like the porphyroid pebbles. Modification is limited to albitisation of felspars (both K-felspar (?) and more calcic plagioclase). These granites show no special characteristics indicative of a known area of provenance and, in fact, since they apparently stem from a granite intrusion or granitisation episode belonging to a *"pre-Kalgoorlie"* orogeny, their parent mass cannot be expected to be exposed at the present time (the Kalgoorlie metamorphic rocks being the oldest known in this part of Australia). These granites do represent one of the earliest known igneous events in Australian geology: with some of the porphyroid and the metasedimentary pebbles, all very similar to the host Kalgoorlie rocks, indicative of another, even earlier geological cycle, we are reminded of Hutton's famous dictum:—

> "The result, therefore, of our present enquiry is that we find no vestige of a beginning, no prospect of an end."

The metasedimentary pebbles may or may not be of rocks metamorphosed before incorporation in the conglomerate. The lack of any high grade assemblages means that, if they were metademorphosed prior to incorporation, the metamorphism was of similar low grade to that pertaining in this area (p. 25). For one cannot believe that this low grade of regional metamorphism would not have left some residual traces of previous high grade index minerals. There is no evidence of polymetamorphism, yet it cannot be ruled out. It is, however, easier to believe that these rocks have suffered but one metamorphism (i.e. while incorporated in the conglomerate). On the other hand they are associated with granites and porphyroids which suggest provenance in a metamorphic terrain.

These metasedimentary pebbles are much modified derivatives of a variety of rocks in which albite shows a rather limited range of variation, in respect of which we must consider the fact that only certain resistant types are likely to survive to be incorporated in a conglomerate of this type. The absence of pelitic pebbles and "greenstone" pebbles has commonly been attributed to the fact that they did not survive, being chemically unstable, liable to attack and destruction by surface agencies. Thus, the total absence of "greenstone" pebbles does not remove the possibility of these conglomerates being at least in part locally derived—certainly some of the metasedimentary pebbles appear very like the host rocks. Against local derivation of the greater part of the pebbles, one must, however, set the fact that this would surely require considerable unconformities in the Kalgoorlie system and these are not all evident in the Lake Lefroy area, though they could have been tectonically "ironed out" (see also discussion, p. 29). Also the granite pebbles, similarly chemically unstable, seem to have survived. The conclusion is reached that only a minor part of the meta-sedimentary pebbles is likely to be of local origin—derived from stratigraphically lower units of the Kalgoorlie system.

The Kaolinised metasandstones—upper part of the Merougil Beds. Description of the Western exposures (based on the Thesis of J. J. G. Doepel (1965) and field notes of G. J. H. McCall).

A few outcrops of kaolinised metasediments occur in the Merougil Creek, the last being near the north-south fenceline about half a mile east of Yilmia Dam, where graded bedding gives a west facing. The rock exposed there is a kaolinised meta-greywacke not unlike those of the Merougil Creek sub-area described by Braybrooke and Middleton. Some of the kaolinised material of the intervening exposures is sufficiently well preserved to allow reasonably certain identification as meta-greywacke. The inference is drawn that the homocline continues almost to Yilmia Dam.

Chemical Analyses.

Chemical analyses by standard rapid methods (suitable for broad comparative purposes) of some of the Merougil metasediments are given in Table 2.

TABLE 2

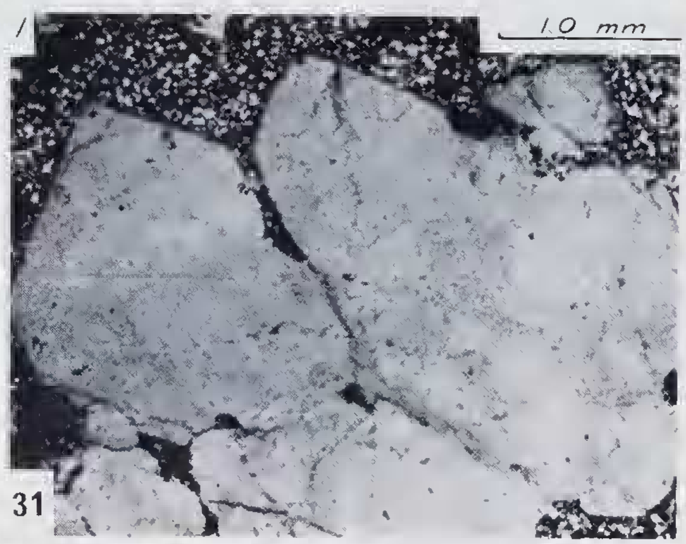
Chemical analyses—Merougil Beds; metasediments

	53006	53021	53059	53066	53034
SiO_2	69.7	73.4	70.7	54.5	62.0
Al_2O_3	13.1	12.0	12.2	12.0	12 9
Fe_2O_3	5.9	6.7	4.9	10.9	6.7
TiO_2	0.7	0.1	0.1	trace	0.9
CaO	2.4	3.4	1.8	9 8	6.4
MgO	0.1	....	1.2	5 6	0.4
Na_2O	5.2	3.2	5 4	3 8	7.4
K_2O	2.8	1.9	1.9	3.0	2.6
P_2O_5	0.1	0 2	....	0.3	0.3
Total	100 0	100 9	98.2	99.9	99.6
	I Meta-sandst. matrix of un-deformed metacongl.	II Matrix of sheared metacongl.	III Porphyroid pebble.	IV Biotite rich metasedt. pebble.	V Basal schist.
Anal.	J.C.B.	D.D.M.	D.D.M.	D.D.M.	J.C.B.

Meta-Igneous Rocks.

The rocks of the Red Hill-Kambalda Ophiolite Belt were not examined in detail. Specimens were collected of actinolitic rocks (metabasalts and metapicrites) and serpentinites from the ridge outcrop at its extreme southern tip, near the Red Hill Mine: and other specimens of actinolitic rocks were collected from the sparse exposures in the low country of virtually no exposure which intervene between the outcrop of the Merougil Beds and Red Hill ridge.

* Associated granite pebbles collected by Glikson have, in fact, now yielded Katarchaean ages (3000-3100 m.y.). Written communication, A. Y. Glikson: Age determination by W. Compston, Australian National University. There are, however, considerable doubts about the validity of this age dating result.



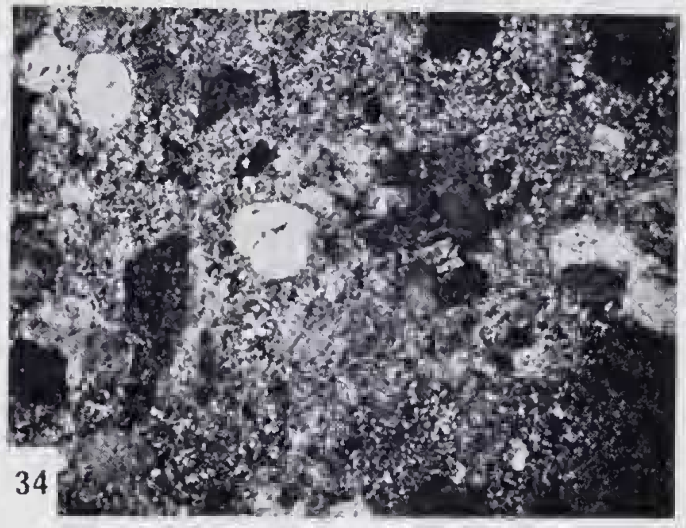


Figure 31.—Quartz phenocrysts in a granodiorite porphyry, shown for comparison; taken from Misch, 1949 p. 388. In both cases prism faces are suppressed, and pyramid faces emphasised, to approach the characteristic form of β-quartz.

Figures 32, 33.—Meta-igneous rocks.—32. Metabasalt, an actinolitic rock with blastophitic texture. The laths of actinolite (grey) are ragged, and the individual grains of the quartz-felspar pools (white) are poorly defined, though laths of felspar, considerably saussuritised are aparent (white) (53081). Plane polarised light, crossed nicols X25). 33. Serpentine-talc rock replaced by dolomite (light grey, rhombs; dark, thin bands are magnetite, which also picks out olivine pseudomorphs in the serpentine talc aggregate (dark grey) (53083) (crossed nicols X10).

Figures 34, 35.—Igneous rocks.—34. Quartz-albite porphyry (53087): albite, dusty grey, twinned; quartz clear, subhedral phenocrysts; both set in a fine, allotriomorphic quartzose matrix carrying some felspar (crossed nicols X10). 35. Porphyritic adamellite (53088): albite phenocrysts, dusty grey, subhedral; set in a fine allotriomorphic matrix of quartz (clear white) and microcline (pale grey) crossed nicols X10).

Figure 36.—Cross bedding in metasandstone of the metasandstone/metaconglomerate sequence.

Specimens from the low country include a medium-grained quartz-biotite-saussurite-actinolite rock (53079), deep-greenish grey and massive, lacking a directed texture. Actinolite (85% by volume), in the form of blade-like interlocking prisms, patches of granoblastic quartz and saussuritised plagioclase are the main mineral constituents; some epidote is associated with the felspare and biotite occurs as small flakes scattered throughout the rock. Relict igneous texture is not apparent, the texture being essentially crystalloblastic. A fine-grained quartz biotite-actinolite rock (53080) from the same area consists predominantly of actinolite (95% by volume); in the form of fibrous needles; biotite (colourless; red-brown) and pyrite make up the remainder of the rock. The lack of felspar in some of these rocks suggests that both basaltic and picritic volcanics were erupted.

In the case of the actual Red Hill ridge, only lake shore exposures were examined, and the petrographic work carried out was mainly concerned with what was believed to be a pattern of progressive metasomatism of the actinolitic rocks (p. 26). 53081 and 53082 are representative of the metabasaltic actinolitic rocks which have not suffered metasomatism (Fig. 32). The former is a blastophitic quartz-saussurite-actinolite rock, which, in hand specimen, appears massive, dense, and of dark greenish-grey colour; there is no apparent structure or texture. It consists of actinolite (X: pale green: Y: light green: Z: blue-green) in the form of stumpy prisms and anhedra. Aggregates of saussuritised felspar are enclosed in the actinolite mat. Magnetite is the only accessory. 53082 carries more biotite (5% by volume) and is appreciably carbonated.

A dolomitised serpentine (53083) from the same area, appears in the field to form part of a pod-like body 10 feet thick. Large knots of dolomite are set in a fine matrix of grey-green, talcose serpentine, each present in nearly equal quantity (Fig. 33). Magnetite crystals have picked out the outlines of a pre-existing mineral, probably olivine: sub-parallel bands of magnetite also traverse the rock which is sparingly punctuated by limonitised pyrite cubes. The rock is presumably a derivative of an ultrabasic igneous rock, such as a peridotite.

The metasomatic derivatives of the basic rocks are discussed below.

The Acid Igneous Rocks.

Extensive outcrops of quartz-albite porphyry and fine-grained granite occur in the Red Hill-Kambalda Ophiolite Belt. Other outcrops of porphyry occur on the lake shore at "Little Italy" and inland from there, within the low country of poor exposure. The evidence suggests that the intrusion of these rocks was not separated by a long interval from the peak of metamorphism, but, rather, they were emplaced in the waning stages of metamorphism and orogenic deformation. The quartz-albite porphyry of "Little Italy" is separated from the lowest of the Merougil Beds by an exposure gap of 600 feet: it is strongly jointed, weathers to angular blocks, has a pale-buff colour in outcrop, and is extremely uniform in texture and composition. Phenocrysts of quartz show clearly, set in a very fine, porcellainous matrix. The few xenoliths of sedimentary rock set in it are apparently of local origin.

53075 is representative of this body: it is weakly foliated (being taken from a shear zone), but little evidence of directional texture is seen in this section. Plagioclase (An_7) forms subhedral phenocrysts ($\leqslant$ 2.5 mm) altered to sericite, especially along twin composition planes and cleavages; and showing albite and Carlsbad twinning. Quartz phenocrysts ($\leqslant$ 3.0 mm), of sub-rounded form, show undulose extinction, and fracturing, together with some stretching and recrystallisation in pressure shadows. There is a very fine groundmass of quartz ($\leqslant$ 0.02 mm), rare biotite flakes, and accesory epidote, tourmaline, muscovite and flakes, and accessory epidote, tourmaline, muscovite and apatite. Numerous quartz veins traverse this porphyry.

The porphyry from the Red Hill-Kambalda ridge shows many signs of intrusive contacts. There is a gradational transition between quartz-albite porphyries and a fine grained adamellite; there being no mappable contact between them. They do not appear to represent separate intrusions. Support for this interpretation is seen at the *"Ringneck Granite"*, a few miles to the north along the same ridge: here fine-grained granite has a marginal zone of quartz albite porphyry (O'Beirne, 1968).

53087 (Fig. 34), from near the Red Hill Mine is a medium to fine-grained quartz-albite porphyry. Milk-white felspar phenocrysts and clear quartz phenocrysts are set in a pale grey, porcellaneous ("Chert-like") matrix containing sparse, small cubes of pyrite. The plagioclase (An_7) forms subhedral phenocrysts ($\leqslant$ 3.0 mm) showing albite and Carlsbad twinning, some sericitisation, and sparse quartz inclusions. The quartz phenocrysts are anhedral to rounded-off subhedral in form, and show embayments. The groundmass is very fine, consisting of lobate and sutured quartz grains, biotite (ragged flakes, $\leqslant$ 0.2 mm), epidote, pyrite and apatite. There is some albite on the groundmass, and the presence of some K-felspar was suggested by staining. The adamellitic rocks, into which the quartz-albite porphyry grades, are represented by 53088, a fine-grained, porphyritic biotite adamellite. Felspar forms small, subhedral phenocrysts, crammed into a fine interstitial base: it is albite (An_{10}), sericitised and showing twinning, mainly on the albite laws. The fine matrix consists of quartz, plagioclase, microcline, biotite, epidote, apatite and pyrite (Fig. 35).

Metamorphism

There is considerable evidence of a complex history involving localised metasomatism superimposed on a regional metamorphism of low grade. The mineral assemblages in the metasediments are: quartz + biotite ($\pm$ albite, epidote, chlorite, muscovite, calcite and pyrite). This indicates assemblages consistently within the *quartz-albite-epidote-biotite subfacies* of the *Green Schist Facies* (only the cordierite, present in a single rock specimen, is anomalous, and this may be due to contact metamorphism). The porphyry boulders of the conglomerates and the porphyry intrusions (which appear to have suffered some metamorphism) show similar assemblages.

The meta-igneous basic rocks have assemblages:—

quartz-biotite-epidote-actinolite
quartz-biotite-actinolite
quartz-epidote-actinolite

compatible with the same sub-facies.

The presence of small quantities of chlorite and sericite is not anomalous (Turner and Verhoogen, 1960, p. 537), but there is some textural evidence that biotite has been converted to chlorite in a late retrogressive phase. Albite is the stable plagioclase, and other plagioclases are virtually absent, original more calcic plagioglases having been converted to it: there are, however, a very few relics of more calcic plagioclase and of original K-felspar. Contact metamorphism is of no significance in this area.

Metasomatism

There is evidence, in the form of numerous veins and replacement zones, of considerable metasomatism of the metasediments, and the micro-textures certainly support this. The metasomatism is envisaged as a front, which moved out from the porphyry intrusives, themselves, in some cases, marginal to a core of fine-grained granite. The evidence for what is essentially a contact metasomatism, but extending over a very large contact zone, lies in the geographical distribution of the metasomatic rocks, and the apparent increase in intensity of the effects close to the intrusions.

The sheared metasandstone/metaconglomerate closely abuts the porphyry of Little Italy and is clearly metasomatised (p. 21). As one moves towards the east (downwards in the succession) the pebbles, sheared, but quite distinct at the western contact with the spotted sandstone, tend to become indistinct, losing their identity by becoming flattened, attenuated and developing merging boundaries with the matrix. At the extreme eastern side of the exposure they become difficult to delineate, the mass becoming almost homogeneous.

During the first reconnaissance of the area a picture of severe metasomatism obscuring the original characteristics, and producing a rock indistinguishable from a porphyry, was suggested: and it was thought possible that the homogeneous porphyry of "Little Italy" with only a few "xenoliths" in the form of pebbles, could be the end-product of this process. Microscopic examination, however, suggests that this is not the case. Metasomatism and homogenisation have undoubtedly occurred, but the metasomatism is not very severe: cataclasis and recrystallisation, always tending towards the smoothing out of irregularities in the rock fabric are the dominant processes in the homogenisation—i.e. the mechanical adjustment outweighs chemical adjustment.

The metasomatism is reflected by tourmaline and epidote occurring both as constituents of the numerous quartz veins and in narrow bands within the highly sheared rocks. The shearing must have facilitated movement of solutions by providing channels. The metasomatic development of albite, quartz and calcite seems also to have some correlation with degree of shearing, and consequent facility of movement of metasomatic agents. The development of spots of various sizes and structures in the spotted metasandstones (p. 13) is further evidence of metasomatism. Goodspeed (1937a, p. 134) has ascribed the development of very similar spots within quartz porphyroblasts to the contact effects of a nearby granodiorite intrusion, and a similar origin is postulated here.

The metaconglomerate above the spotted metasandstone shows some evidence of metasomatism in a modification of the pebbles revealed in this section (p. 17), but no megascopic evidence other than veining.

The metasomatism seems to have involved introduction of soda and silica, and produced growth of new porphyroblasts, regrowth of quartz and albite phenocrysts in the pebbles, and conversion of original felspars to albite. The abundant biotite inclusions within the felspars (p. 17), are ascribed to this process. Porphyroblast development produced new large crystals within both pebbles, and to a lesser extent, the conglomerate matrix. Quartz-albite-epidote-tourmaline veins developed at the same time. The metasomatic process is regarded as the incipient stage in the more extreme metasomatic process recognised further south by McCall, Muhling and O'Beirne (Muhling, 1965: O'Beirne, 1968: McCall and Muhling, and McCall and O'Beirne, parts IV and V of this series of accounts [in preparation]).

The metasomatism of meta-igneous rocks of the Red Hill-Kambalda Ophiolite Belts

Near the contact between metamorphosed basic volcanics and porphyry at the Red Hill Mine, what has been supposed to be progressive metasomatism has been studied in its stages of development (Braybrooke and Middleton, 1964). Soda and silica introduction was believed to have produced quartz and albite porphyroblasts within the metamorphosed basic rocks.

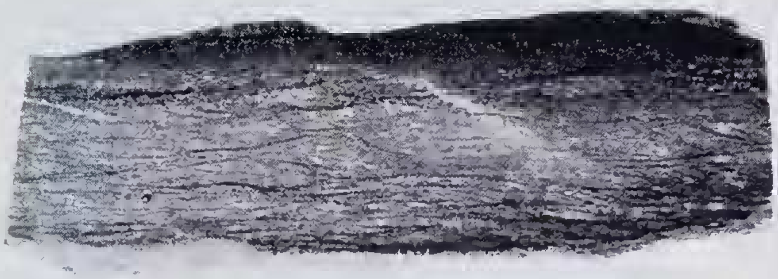
Since this metasomatism was studied by Braybrooke and Middleton, O'Beirne (1968) has queried these authors' conclusions. He is of the opinion that the pronounced zoning in the felspar of supposed metasomatic products indicates that these are igneous porphyries, and he supports this contention with chemical analyses which do not favour progressive metasomatism to this end-stage product, but indicate that this rock is chemically similar to certain dacitic igneous rocks which occur at Kalgoorlie. His interpretation requires the supposed end-stage product to be a dacitic porphyry, cutting the rocks of the ophiolite belt. He accepts a limited amount of contact metasomatism related to this body.

Structure

The structure of the main sedimentary sequence is homoclinal, steeply dipping to the west, and west facing. The regional structure, a synclinorium, is discussed in Part 1 of this series of accounts (McCall, in the press). The evidence for the dislocation supposed to separate the Merougil Beds from the Red Hill-Kambalda Ophiolites is in the increased deformation recognised close to this line, and the apparent wedging out of the stratigraphy revealed by regional mapping to the north. This dislocation may well be the southerly extension of the Boulder Fault which separates the Mt Hunt Ophiolites from their supposed equivalent on the east side of the fault, the Kalgoorlie Ophiolites (which are themselves in strike continuity with the Kambalda Ophiolites).

An anticlinal dome has been recognised during mining operations at Kambalda, and pillow lavas in the metabasalts face antithetically east and west, off this dome.

The minor tectonic structures within the Merougil sub-area are limited to a few small, gentle flexures in the Merougil Beds; some fracture cleavage in the finer members: and east-west joints, which are common and are frequently filled with vein quartz. An interesting feature is the set of these joints which traverse the conglomerates of the upper unit, cutting through boulders and matrix like a knife cut, and are vertically disposed (Fig. 43).



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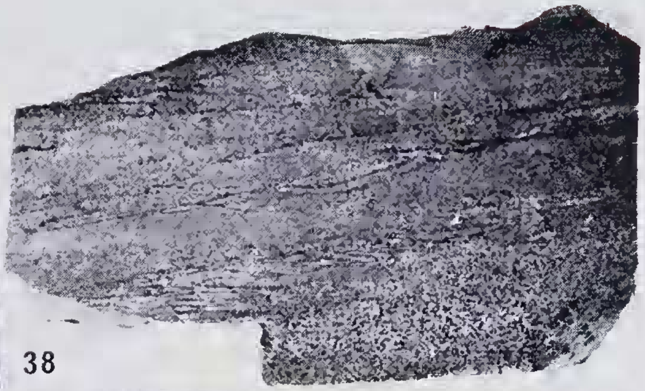

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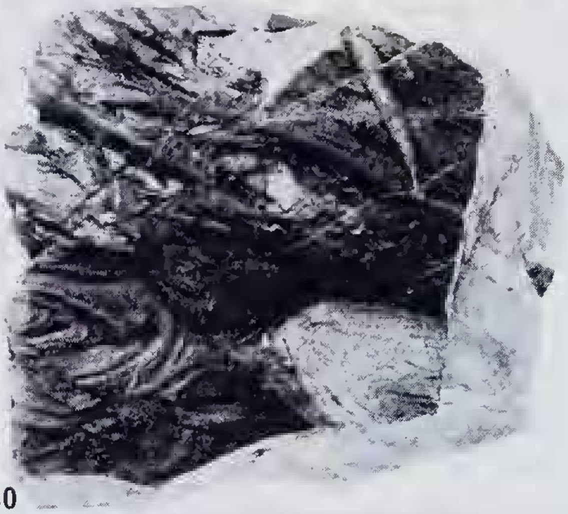

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Figures 37-41.—Primary sedimentational structures.—37. Micro-crossbedding (the specimen is 9½ inches long): (53043 from the fine grained metasandstone). 38. Micro-crossbedding in a fine metasandstone (53003) showing associated grading of biotite flakes (the specimen is 4 inches long). Microfaulting of primary sedimentationed origin is also evident. 39. Laminated, elongated, ball and pillow structure in fine-grained metasandstone/metasiltstone (53045): the truncation is by penecontemporaneous erosion. The specimen is 10 inches long. 40. Laminated ball and pillow structure, producing a pseudo-concretionary character in the rock, a fine-grained metasandstone/metasiltstone (53046): the face shown measures 4 x 4 inches. 41. Contorted bedding in a fine-grained metasandstone band.

Figure 42.—Bedded fine-grained metasandstone showing some fracture cleavage.

Deformation of the conglomerates.

The sheared sandstone conglomerate shows abundant evidence of deformation by strong shearing stresses (Fig. 43). The pebbles are deformed to varying degrees, as is the matrix. The most noteworthy feature is the inhomogeneous distribution of the effects of the shearing strain, due to the initial inhomogeneity of the rock. The pebbles in the sheared conglomerate are ellipsoidal with longest and intermediate dimensions in a plane parallel to the strike and the smallest dimension normal to it. Measurement of the pebbles axes were carried out mainly on joint planes exposing flat rock surfaces, but in some cases the pebble had to be separated from the matrix to make the third measurement. Two localities, A and B, both in the sheared conglomerate unit outcrop, were sampled (Fig. 2). This investigation (by D.D.M.) is fully recorded in the thesis (Braybrooke and Middleton, 1964): it is not possible to give more than the bare results here. The method is based on studies by Cloos (1947), Oftedahl (1949) and Flinn (1956). The technique adopted was that used by Oftedahl. The results show that at point A the original statistical sphere has not suffered any extension of the second axis b in respect of axis a. The deformation is consistent with *simple shear* deformation. In contrast at point B there has been an extension of the axis b in relation to a, in addition to the deformation in c Thus, at A, a is extended and c shortened, the effect at B is extension of both b and a, but a slightly more than b, and c is greatly shortened.

Following the interpretation of Flinn for similar deformations, it is supposed that at B pressure (such as alone would produce an oblate spheroid) perpendicular to the direction of maximum elongation (to the ab plane) has operated in addition to simple shear. Patterns of fracturing of pebbles from the creek support the idea that such pressure has operated. Such patterns (Fig. 4) resemble those described by Ramsay (1964, p. 228) from near the Highland Boundary Fault, Scotland. They include unidirectional wedge fracturing (with or without displacement), and radical cracking (Fig. 45).

Dumbbell shaped pebbles are not uncommon (Fig. 48) in the extremely sheared conglomerates. The long dimension of such dumbbells never lies parallel to c, but can lie anywhere in the a, b plane. They are attributed to compression and fracturing (Fig. 5) and are conspicuous at point B, where pressure has operated in addition to *simple shear*. *Brittle fracturing* has been followed by a continuation of the same deformation *in a plastic* or *near-plastic* state. There is increased elongation in the directions already established, thinning out and necking.

This work does suggest that point B should, on theoretical grounds be very near to a fault plane or zone (p. 26).

Primary Sedimentation

Primary depositional structures.

Cross-bedding. Trough cross-bedding (Figs. 36, 37) is present throughout the Merougil Beds. It invariably shows west facing. The sets are 1″-9″ thick and the forsets straight or concave down-current, which indicates a predominantly unidirectional current rather than an oscillatory one (Harms et al, 1965). Stream channel deposits, deltaic distributory channel deposits, and near shore marine deposits, where slopes have an appreciable angle to the surface of aggradation (Dunbar and Rodgers, 1961, p. 188) commonly show abundant cross-bedding of this type. The current rose produced for this type of structure will indicate not only the directions of current movement but also the trend towards deeper water. In rare cases, graded bedding accompanies cross-bedding (Fig. 38).

Ripple-marks. A few poorly formed, symmetrical ripple marks were noted in the fine-grained metasandstone. They are attributed to wave-generated oscillating currents (Pettijohn, 1957, p. 2186).

Soft Rock Deformations.—These include load casts or pockets indicating only vertical movements: asymmetrical load casts indicating both vertical and lateral movement: and ball-and-pillow structures which are a development of the latter. No particular environment is indicated by such structures: Potter and Pettijohn (1963, p. 147) suggest the requirement is simply any sand bed on a water-saturated hydroplastic layer, but Kelling and Walton (1957, p. 487), suggest that unequal loading, due to irregularities in the upper surface of the underlying fine bed, is involved. The origin of the ball-and-pillow structures is debatable. Kay and Power (1963) invoke foundering of a sand layer into mud: Potter and Pettijohn (1963) following Kuenen (1958), suggest the requirement of seismic triggering.

The ball-and-pillow structures, where truncated (Fig. 39), show a typical synclinal cut-off which gives a good facing indication: in this case always consistent with the cross-bedding.

Complex pseudoconcretionary convolutions (Fig. 40) may be related to penecontemporaneous turbulence causing rolling, and subsequent flattening, during compaction. Contorted bedding is also present (Fig. 41) of the type that Sutton and Watson (1960, p. 116) consider to be due to quicksands, disturbed as the water is driven out. Graded bedding is not very common, though in one case it has been recorded, where it is internal to cross-bedding.

Microfaulting of primary origin and *imbrication structure* (Potter and Pettijohn, 1963, p. 26) are other primary structures noted.

Depositional environment

The area appears to have been marginal to a geosyncline. Early Precambrian geocynclinal furrows were probably long and narrow (Pettijohn, 1943, Wilson 1958).

The *slates* are pelitic metasediments: the presence of possibly primary pyrite and also graphite does not necessarily require anaerobic conditions for it is now commonly supposed that a reducing, anoxygenic atmosphere pertained at this early date (Rutten, 1962). Such ancient pyritic and graphitic rocks could well have been deposited in a marine geosynclinal basin. The pelitic rocks presumably reflect deepening of the environment.

The *metasandstones* (Fig. 42), though largely modified in texture by metamorphism and metasomatism, show enough of their original texture for one to be satisfied that they were originally poorly-rounded "dirty" arkoses (Pettijohn, 1957, p. 332). Such sediments will have become predominant as the source land mass area suffered maturation of its relief, and its streams lost their transporting capacity. Thin pebble bands which appear abruptly in the sequence and disappear equally abruptly may reflect periods of increased precipitation rather than tectonic disturbance.

The texture of the finer sandstones suggests periodic rather than continuous sedimentation, with finer material deposited after an initial period of coarse sedimentation. There is much evidence of lateral gradation, suggesting quiet water conditions allowing differential settlement. The sedimentary structures within these beds suggest quiet conditions, with intermittent rougher periods.

There is no direct evidence that these finer psammitic sediments are marine: but the overall association rules out lacustrine deposition; and the great thickness of similar rocks seems to rule out fluviatile deposition. The deposition may have been estuarine, or paludal: or a combination of both.

The *metaconglomerates* (Fig. 43) are petromict or polymictic (Pettijohn, 1957, p. 256-7), having an intact "framework" of plutonic, ruptive, and sedimentary pebbles with varying amounts of an interstitial sandy matrix, often converted to a secondary calcitic cement. Coarse, strongly cross-bedded metasandstone lenses and beds are intimately associated with the metaconglomerate (Fig. 44), indicating deposition from highly turbulent waters. High-velocity streams or surf are possible.

The boulders are moderately to well rounded (Fig. 45) averaging 2-5 inches long—though some three feet long occur as rare isolated individuals (Fig. 46). The mean size is one tenth of the maximum, as is common in conglomerates (Pettijohn, 1957, p. 258). The rounding of pebbles cannot be taken as definitely indicating long transport (Krumbein, quoted in Pettijohn, 1943, p. 935). The presence of granite boulders, relatively unstable to chemical and mechanical weathering, indicates that disintegration and solution were subordinate (there is, as has been noted, an interesting bearing of this conclusion on the common explanation for the absence of "greenstone" boulders p. 23). This suggests high relief and rapid erosion for the source land mass at the time of deposition. Pettijohn (1957, p. 257) regards the presence of granite debris as indicative of major uplift, as opposed to granite free conglomerates, which may record only a minor interlude in the history of the basin of deposition.

The sedimentary pebble content indicates that a large area of the source land mass was covered by sedimentary rocks. The thickness of the conglomerates is notable, and they could be a basin margin accumulation of outwash gravel, shed from sharply elevated highlands in the foreland. The nature of the pebbles and matrix, and lack of volcanic fragments suggests a continental foreland, not an island arc land mass of temporary elevation. The material was probably moved by both stream discharge and long shore current transportation. The palaeo-current measurements are not considered to support the idea of deposition from a great river as suggested by Maclaren and Thompson (1913).

The abundance of similar conglomeratic beds throughout the considerable thickness of rocks of the Kalgoorlie system between Kurrawang and Widgiemooltha does not seem compatible with fluviatile origin, nor does the scale of the cross-bedding structures.

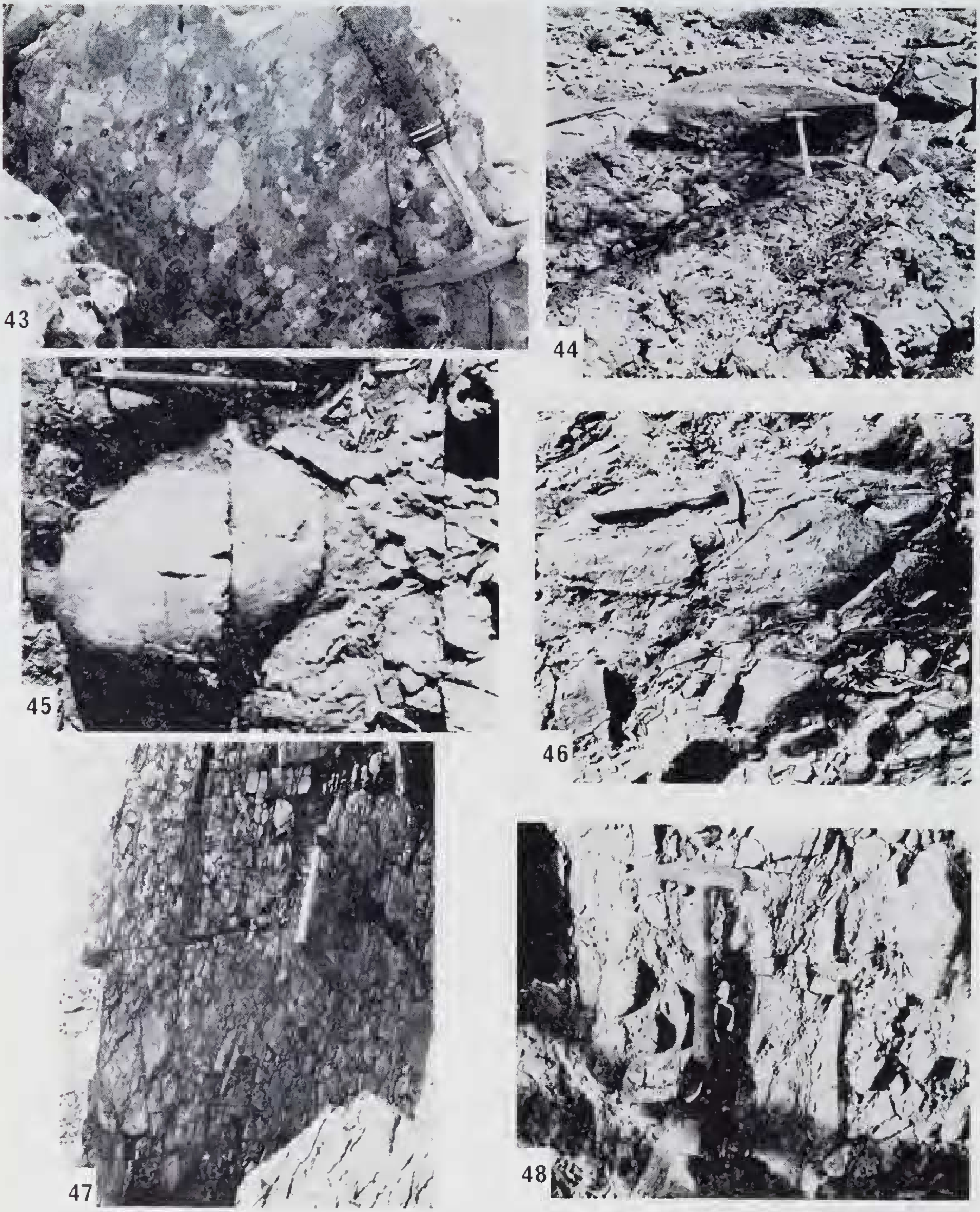
Angular boulders are abundant (Fig. 47) in the sheared and "homogenised" metaconglomerates—some exceeding six-feet in length. These can have had little transport, and must be of local provenance. Some geologists have suggested that these deposits are volcanic breccias rather than ruditic metasediments.

Current directions

A pilot study (table 3) was made (by J. C. B.) of the current directions. The technique used is described in the thesis (Braybrooke and Middleton, 1964). The rocks are difficult to work on, because the bedding planes are welded and separation of specimens for measurement is far more difficult than in unmetamorphosed sandstones. Only 15 measurements have been made, as against 25-30 recommended by Potter and Pettijohn (1963, p. 263).

The "current rose" obtained (Fig. 6) does suggest off-shore, north-eastwards directed currents predominated, though westerly directed long-shore currents were also active in the basin of deposition. The main currents were probably of stream or shallow marine origin, moving outwards from highlands situated to the south-west. All the evidence available supports the idea that the basin did deepen towards the east at the time of conglomerate deposition, as suggested by Horwitz and Sofoulis (1965). This evidence supports the conclusion that the present elongated outcrop of conglomerates in the area west of Kalgoorlie is not directly related to the shape of the basin of deposition, but reflects the tectonic structure, the upper and more conglomeratic members of a thick stratigraphic sequence being exposed in a synclinal zone.

The area is not unlike the Abram Lake Area of Ontario, Canada (Pettijohn, 1934), which Pettijohn attributed to non-marine, piedmontine deposition in a subsiding trough. All the evidence from this area seems to favour a similar



Figures 43-48.—Field appearance of the metasandstones and metaconglomerates.—43. Metaconglomerate cut by knife-sharp parallel joints normal to the strike, joints which slice cleanly through matrix and pebbles. The polymictic character and rounding of the phenoclasts are apparent. 44. Metaconglomerate/metasandstone alternation near the bottom of the metasandstone/metaconglomerate sequence. 45. A large fractured pebble in the metaconglomerate (pencil gives scale). 46. a boulder over three feet long in the metaconglomerate (from an outcrop in the Merougil Creek section). 47. Deformed, partly homogenised metaconglomerate. 48. Deformed metaconglomerate showing large dumbbell shaped pebbles, with a constriction in the middle section (from an outcrop in the Merougil Creek section).

piedmontine setting, but deposition in an off-shore marine environment. The lack of volcanic fragments in the meta-greywackes suggests a foreland shoreline, rather than an island arc shoreline environment.

TABLE 3

Cross-bedding Measurements

Position	True Bedding		Cross-Bedding			
	Strike	Dip	Inclination	Thickness	Azimuth	Corrected Azimuth
1250S 1450E	310°	53° SW	23°	4″	110°	067°
1350S 1520E	325°	70° SW	20°	7.5″	058°	054°
1120S 1460E	320°	80° SW	18°	9″	310°	277°
1540S 3430E	325°	65° SW	27°	4″	120°	096°
0850S 2210E	344°	70° SW	14°	2″	072°	075°
1100S 2070E	325°	52° SW	38°	6″	298°	286°
1300S 1500E	320°	55° SW	20°	7″	070°	083°
1300S 1500E	318°	72° SE	22°	7″	048°	048°
1300S 1500E	....	....	.	....	067°	050°
0390N 6400N	310°	55° SW	22°	....	300°	292°
0240N 5880W	320°	64° SW	20°	....	305°	298°
1980S 4770E	320°	70° SW	28°	9″	025°	042°
1250S 6530E	325°	65° SW	26°	....	030°	044°

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